NASA Contractor Report 4526

Design and Application of a Quasistatic Crush Test Fixture for Investigating Scale Effects in Energy Absorbing Composite Plates

J. André Lavoie and John Morton
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Prepared for
Langley Research Center
under Grant NAG1-343

NASA
National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Program
1993

DESIGN AND APPLICATION OF A QUASISTATIC CRUSH TEST FIXTURE FOR INVESTIGATING SCALE EFFECTS IN ENERGY ABSORBING COMPOSITE PLATES

by

J. André Lavoie, graduate student

and

John Morton, Professor

Engineering Science and Mechanics Department
Virginia Polytechnic Institute and State University

ABSTRACT

A crush test fixture for measuring energy absorption of flat plate specimens from an earlier study was redesigned to eliminate the problem of binding of the load transfer platen with the guide posts. Further modifications were to increase the stroke, and combine the two scaled test fixtures into one. This new crush test fixture was shown to produce load-displacement histories exhibiting well developed sustained crushing loads over long strokes.

An experimental study was conducted on two material systems: AS4/3502 graphite/epoxy, and a hybrid AS4-Kevlar/3502 composite. The effect of geometric scaling of specimen size, the effect of ply-level and sublaminate-level scaling of the stacking sequence of the full scale specimens, and the effect of trigger mechanism on the energy absorption capability were investigated.

The new crush test fixture and flat plate specimens produced peak and sustained crushing loads that were lower than obtained with the old crush test fixture. The trigger mechanism used influenced the specific sustained crushing stress (SSCS). The results of this study indicated that to avoid any reduction in the SSCS when scaling from the 1/2 scale to full scale specimen size, the sublaminate-level scaling approach should be used, in agreement with experiments on tubes. The use of Kevlar in place of the graphite 45° plies was not as effective a means for supporting and containing the 0° graphite plies for crushing of flat plates and resulted in a drop in the SSCS. This result did not correlate with that obtained for tubes.

TABLE OF CONTENTS

ABSTRACT iii
TABLE OF CONTENTS vi
LIST OF TABLES vii
LIST OF FIGURES viii

Chapter — Page

1. INTRODUCTION 1
   1.1 Statement of the Problem 1
   1.2 Summary of Previous Work 1
   1.3 Organization of the Report 3
2. DEVELOPMENT OF A CRUSH TEST FIXTURE 4
   2.1 First Generation Crush Test Fixture 4
      2.1.1 Assessment of Performance 4
      2.1.2 Attempts to Alleviate Problems 4
   2.2 Second Generation Crush Test Fixture 5
      2.2.1 Design Features and Improvements 5
      2.2.2 Commissioning 5
3. ENERGY ABSORPTION OF COMPOSITE PLATES 7
   3.1 Experimental Details 7
      3.1.1 Materials 7
      3.1.2 Specimen Fabrication 7
   3.2 Experimental Results 9
      3.2.1 AS4/3502 Graphite/Epoxy 9
      3.2.2 AS4/Kevlar-49/3502 Hybrid Graphite-Kevlar/Epoxy 11
      3.2.3 Comparison between the AS4/3502 and AS4/Kevlar-49/3502 12
4. DISCUSSION OF RESULTS 13
   4.1 Test Fixture Performance 13
   4.2 Observations On Crushing Behavior 14
      4.2.1 Effect of Trigger Mechanism on Peak and Sustained Crushing Loads 14
      4.2.2 Effect of Scale on Peak and Sustained Crushing Loads 14

4.2.3 Plate Energy Absorption and More Complex Structures............ 15
5. CONCLUDING REMARKS 17
6. REFERENCES 18
7. APPENDIX 46
A.1 Engineering Drawings 46

LIST OF TABLES

Page

Table 1. Summary of Experimental Data 19

LIST OF FIGURES

Page

1.1 Energy absorbing helicopter subfloor structure.......................................20

1.2 Energy absorbing beam concepts...21

1.3 Idealized load verses displacement response for crushing of a composite cylinder...22

2.1 First generation crush test fixture...23

2.2 Typical crushing response of a composite plate specimen in the first generation crush test fixture. Note the runaway rise in load, indicative of binding within the test fixture.......................................24

2.3 Sideview of the baseline model of the first generation test fixture with a cutout machined into the plate support posts. Purpose was to provide an adjustable size gap for debris to accumulate in...25

2.4 Crushing response of a composite plate in the old crush fixture, but with 3/16" of the plate unsupported...26

2.5 New test fixture configured for baseline or 1/2 scale specimens.................27

2.6 New test fixture configured for full scale specimens.................................28

2.7 Baseline-configured test fixture with loading rod and diameter-reduction adapter attached...29

2.8 Typical crushing response of a composite plate specimen in the new crush test fixture. Note the steady sustained crushing load and long stroke...30

2.9 Crushing response of baseline Gr-Kv/Epoxy plates with steeple trigger mechanism in the (a) old fixture and (b) new fixture.......................31

3.1 Schematic of baseline, ply-level, and sublaminate-level scaled plates in cross-section (steeple trigger shown).......................................32

3.2 Typical laminate cure cycle...33

3.3 Schematics of trigger mechanism used in the baseline specimens (triggers for full scale specimens are doubled in dimension). 34
3.4 Strain gage placement on the baseline plate. 35
3.5 Effect of scaling on crushing response of baseline, sublaminate-, and ply-level scaled AS4/3502 plates with (a) steeple and (b) notch triggers. *Loads and displacements have been scaled. 36
3.6 Summary of crushing data AS4/3502 with (a) steeple trigger mechanism and (b) notch trigger mechanism. 37
3.7 Typical strain vs. displacement response of (a) ply-level scaled and (b) sublaminate-scaled AS4/3502 with steeple trigger mechanism. 38
3.8 Effect of scaling on crushing response of baseline, sublaminate-scaled, and ply-level-scaled AS4/Kevlar/3502 plates with (a) steeple triggers and (b) notch triggers. *Loads and displacements have been scaled 39
3.9 Summary of crushing data: AS4/Kevlar/3502 with (a) steeple and (b) notch trigger mechanism. 40
3.10 Comparison of crushing response of typical AS4/3502 and AS4/Kevlar/3502 baseline plates with (a) steeple and (b) notch triggers. 41
3.11 Comparison of crushing response of typical AS4/3502 and AS4/Kevlar/3502 ply-level-scaled plates with (a) steeple and (b) notch triggers 42
3.12 Comparison of crushing response of typical AS4/3502 and AS4/ Kevlar/3502 sublaminate-scaled plates with (a) steeple and (b) notch triggers. 43
3.13 Comparison of peak crushing load for AS4/3502 and AS4/Kevlar/3502 with (a) steeple and (b) notch trigger mechanisms. 44
3.14 Comparison of average crushing load for AS4/3502 and AS4/Kevlar/3502 with (a) steeple and (b) notch trigger mechanisms. 45

A.1 Sliding plate..47
A.2 Base plate..48
A.3 Small knife edge and support post. 49
A.4 Large knife edge, guide post, and support post. 50
A.5 Small support post restraint...51
A.6 Large support post restraint...52
A.7 Load applicator rod..53
A.8 Load applicator extension rod..54
A.9 Load applicator retaining plate...55
A.10 Load applicator centering plate...56

1. INTRODUCTION

1.1 Statement of the Problem

As manufacturers of rotorcraft and light, fixed wing aircraft have turned their attention toward construction of more crashworthy structures, there has been a growing need for inexpensive test methods for studying the energy absorption capability of composite structural elements. For the candidate test method to be truly cost effective, it should be designed to test flat plate specimens. In addition, a test which allows for screening of candidate material systems, optimum lay ups, and alternate trigger mechanisms is needed. The test should also permit the study of scaling effects because researchers usually seek to reduce the test specimens' size to save on material costs. The test fixture described in this report represents a cost effective attempt to meet these criteria.

1.2 Summary of Previous Work

Crashworthiness of vehicle structures is necessary in order to protect occupants against injury and minimize equipment damage in the event of a crash. The U.S. Department of Defense [1] defines crashworthiness as "a crash in which the range of impact conditions, including pulse rate of onset, magnitude, direction and duration of accelerative forces, transmitted to the occupants does not exceed the limits of human tolerance for survival and in which the structure surrounding personnel remains sufficiently intact during and after impact to permit survival". Once a definition of a survivable accident is given and the maximum allowable accelerations that the occupants are expected to survive are specified, the structure can be designed for crashworthiness.

Designing for crashworthiness requires a total systems approach, that is, each part of the structure is designed to dissipate a portion of the energy of a crash so that together they meet the guidelines for crashworthiness. Och prepared a comprehensive review of the broad range of crashworthiness issues and considerations for helicopters [2]. Crushing of the vehicle structure, i.e. a helicopter's subfloor structure, is one of the primary means for absorbing crash energy. Figure 1.1 [3] schematically illustrates the location of the energy absorbing subfloor structure on a helicopter as well as the subfloor construction. Several energy absorbing beam concepts that might be used in constructing the subfloor are shown in Figure 1.2 [3]. In each, the construction is such that progressive crushing instead of global buckling occurs. Farley [3] identified and defined the several crushing modes. These are transverse shearing, lamina bending, and local buckling.

In the transverse shearing crushing mode short interlaminar and longitudinal cracks not longer than the laminate thickness arise, forming partial lamina bundles. These bundles fracture as the bending stress on the tension side of the bundle exceeds the material strength. The fracturing of the lamina bundles is the principal energy absorption mechanism in this crushing mode.

The lamina bending crushing mode is characterized by the growth of long interlaminar and intralaminar cracks that grow at least an order of magnitude greater than the laminate thickness. The laminae bend and spread outward without fracturing fibers. The principal energy absorption mechanism in this crushing mode is by crack formation.

The brittle fracturing crushing mode is a combination of the transverse shearing and lamina bending crushing modes. Crack formation is between one and ten laminate thicknesses with lamina bundle fracture being the major energy absorbing mechanism and lamina bending the inefficient mechanism. This is the mode in which crushing of brittle composite tubes generally occurs, and is also the crushing mode of the flat plates tested in this study. The third crushing mode, the local buckling mode, occurs in materials which have a higher matrix failure strain than the fiber, the interlaminar stresses are small compared to the strength of the matrix, and the matrix yields plastically under high stress. The high strain-to-failure of the matrix discourages interlaminar cracking and promotes local buckling.

An idealized load versus displacement plot is given in Figure 1.3. Typical crushing behavior is characterized by load rising to some peak value followed by an initial failure, and then a sustained crushing load that cycles about some average value that has been suggested by Jones and Carden [4] to be at least 80% of the peak load. The specific sustained crushing stress (SSCS) is a convenient measure of the energy absorption capacity of composite structures. It is defined as the average or sustained crushing load divided by the product of the cross-sectional area of the test specimen and the material density.

Work performed by Farley [3] indicated equal or superior energy absorption capability of hybrid graphite-Kevlar-epoxy beam structures relative to aluminum beams of similar geometry. Stacking sequence was shown to have a strong influence on the energy absorption capability, and variation by as much as 300% was recorded.

1.3 Organization of the Report

In Chapter 2 an assessment of the performance and problems of the first generation crush test fixture are given, then a new design is introduced and qualified. Chapter 3 covers the application of the new test fixture to the measurement of the energy absorption of composite plates made from two material systems: AS4 graphite/3502 epoxy, and a hybrid AS4 graphite-Kevlar-49/3502 epoxy. Specimen fabrication is covered first, the details of the testing procedure is given, and then the experimental results are presented with observations. The results are discussed in Chapter 4. First suggestions for improving the test fixture are listed, then observations on crushing behavior are made as well as the effects of scale and trigger mechanism on energy absorption. Brief comments and correlations between the flat plate test and tests of tubes are made.

2. DEVELOPMENT OF A CRUSH TEST FIXTURE

2.1 First Generation Crush Test Fixture

2.1.1 Assessment of Performance

As already pointed out, the load-displacement response for the crushing of a composite cylinder is approximately constant. Tests using the first generation of flat plate crush test fixtures (old fixture), see Figure 2.1, revealed that the SSCS was not constant but instead rose steadily, as shown in Figure 2.2 (test data are from C. Traffanstedt's masters thesis, VPI&SU, Blacksburg, VA, expected 1993). The design of this fixture is simple: The movable platen slides on four guide posts which are fixed in a base plate. A test plate is slipped between the guide posts which now are doubling as plate supports (the support prevents global buckling and facilitates progressive crushing). Strain in the platen guide posts was measured during a crush test and an increasing compressive strain, which could be correlated with the rising load, was revealed. This indicated that the platen was jamming with the guide posts. Debris accumulation between the guide posts was thought responsible for the jamming, so an attempt was made to relieve the side load on the guide posts.

2.1.2 Attempts to Alleviate Problems

A place for debris to accumulate was provided by machining cutouts in the guide posts (see Figure 2.3). This approach proved counterproductive, as is readily observed in Figure 2.4. The cutout had become an unsupported zone of the plate, which changed its failure mechanism from crushing to one characterized by splitting and delamination. A new test fixture was designed which eliminated any possibility for the platen to jam with the guide posts.

2.2 Second Generation Crush Test Fixture

2.2.1 Design Features and Improvements

The second generation of flat plate crush test fixtures (new fixture) is illustrated in Figures 2.5 and 2.6. In Figure 2.5, the fixture is configured for crushing 1/2 scale, or baseline plates, whereas in Figure 2.6 the fixture is configured for testing full scale plates. Its distinguishing feature is the addition of a set of posts whose only function is to guide the platen. The platen is fitted with linear bearings for near frictionless travel on the guide posts. The posts which provide support to the plate have no contact with the platen. The specimen is in contact with, and supported by, knife edges that fit into keyways in the support posts. The knife edges can be shimmed to accommodate baseline plates less 0.090" thick, and full scale plates less than 0.180" thick. The collar placed over each pair of support posts has two functions. One is to ensure that the specimen is supported along its entire length by eliminating any spreading of the posts that occurs when a plate is crushed. The second is to ensure that the posts do not come into contact with the platen. In Figure 2.7 the test fixture is resting in a universal test machine with the load applicator accessories mounted to the crosshead. A complete set of engineering drawings of the crush test fixture and accessories is included in the Appendix. The load-displacement response of flat plates crushed in the new fixture is similar to the ideal response of self-stabilized composite cylinders.

2.2.2 Commissioning

The typical crushing response of a composite plate specimen in the new fixture is shown in Figure 2.8. The sustained crushing load can be measured well over 3 inches, which is much longer than the 3/4" maximum stroke obtained with the old fixture, and is long enough to develop fully the sustained crushing load. It is noted here that for crosshead displacements over 3 inches some composite plate specimens were observed to completely delaminate. Identical baseline plates were tested in the old fixture and in the new fixture (Figures 2.9). The graphs in the two figures were scaled identically to emphasize the difference in displacement over which the sustained crushing load can be measured, as well as general load-displacement response differences in the two fixtures. The peak loads and sustained crushing loads are lower for the new fixture because the geometry of support is different. There is an increase in the spacing of posts from 1.5" to 1.75" for the baseline test (double for full scale), and there is a change from direct post contact with the plate specimen in the old fixture to knife edge contact for the new fixture. The fixture was designed to test two sizes of plate specimens, baseline (or 1/2 scale) and full scale, these terms having been mentioned previously. The baseline plates have all dimensions reduced to one half the full scale plates. The parts of the test fixture related to supporting the plate specimens have also been scaled. Further discussion of scaling can be found in references [8], and [9].

3. ENERGY ABSORPTION OF COMPOSITE PLATES

3.1 Experimental Details

3.1.1 Materials

Two material systems were evaluated: a graphite/epoxy composite, AS4/3502 (Gr/Ep), and a hybrid graphite-Kevlar/epoxy composite, AS4/Kevlar-49/3502 (Gr/Kv/Ep). Farley's [3] experiments with cylindrical tubes indicated that a graphite-Kevlar epoxy hybrid could produce high SSCS values greater than 100 Nm/g. He found that the SSCS was not particularly sensitive to the number of 0° plies grouped together. A difference of less than 3% was observed for laminates with from three to nine graphite plies blocked together. Based on these results, the laminate stacking sequence chosen was $[\pm45/0_4/\pm45]_s$ for the Gr/Ep baseline plates, and $[\pm45Kv/0_4Gr/\pm45Kv]_s$ for the hybrid baseline plates. Two aspects of scaling were used, in-plane and thickness. Thickness was scaled by ply-level and sublaminate-level approaches, depicted schematically in Figure 3.1. For the ply-level scaled plates the stacking sequence was $[45_2/-45_2/0_8/45_2/-45_2]_s$, while the stacking sequence for the sublaminate scaled plates was $[\pm45/0_4/\pm45]_{2s}$. The Gr/Kv/Ep scaled laminates were similar to the Gr/Ep plates except all 45° plies were Kevlar. Since this project was a continuation of ongoing work performed by Jackson *et al.* [5], the plate dimensions used were not changed and were 2.0" x 3.0" for the baseline plates, and 4.0" x 6.0" for the scaled plates. These plate dimensions were selected such that crushing occurred before global buckling and was based upon a buckling analysis [5]. The nominal specimen thickness was 0.080" for the Gr/Ep, and 0.090" for the Gr/Kv/Ep; the difference in thickness was due to the greater thickness of the Kevlar prepreg. The Gr/Kv/Ep specimens were available from a previous study [5], so the description of fabrication that follows applies to the Gr/Ep plates.

3.1.2 Specimen Fabrication

The flat panels were laid up on a vacuum debulking table, then the laminates were cured in a "press-clave". A press-clave is a miniature autoclave which provides for vacuum to the laminate to remove air and other volatiles, and a hydrostatic pressure to consolidate the laminate into a high quality, void free part. The temperature controlled press is used to provide both the heat needed to cure the laminate as well as the 25,000 lb clamping force used to overcome the 86 psi hydrostatic pressure within the miniature autoclave. The cure cycle was a standard two-step 350°F cure cycle recommended by the material supplier. A typical temperature-pressure-vacuum vs. time cure cycle is shown in Figure 3.2. First vacuum was applied to the laminate. The temperature was ramped up at about 4.5°F/min. to 275°F and held for 15 minutes. Then pressure was applied in three steps: 0 to 30 psi, 30 to 60 psi, and 60 to 86 psi over about a 10 minute period. The reason for this unusual approach to applying pressure was unrelated to the dictates of the cure cycle, but was peculiar to the press-clave and the methods necessary to apply and maintain the hydrostatic pressure. Temperature and pressure were held constant for 45 minutes. Temperature was then ramped up to 350°F, and held constant for 2 hours. The vacuum pump and heaters were switched off, and the laminate was allowed to cool at a very gradual pace of about 1°F/min.

Cured laminates were then cut into coupon specimens (plates) using a diamond wheel cutoff saw with liquid cooling. Blank plates were then given either a steeple or a notch crush initiating trigger mechanism, as illustrated in Figure 3.3. The triggers are the same as used by Jackson [5], and were selected based upon work done by Hanagud *et al.* [6]. The chamfer trigger was not used because Jackson's results indicated that it did not produce a well defined peak load prior to dropping to the sustained crushing load. One plate from each condition was instrumented with Micro-Measurements CEA-03-250UW-350 strain gages. The location of the gages is shown in Figure 3.4.

Quasi-static crush tests were performed using the new fixture on baseline, ply-level scaled, and sublaminate level scaled Gr/Ep and Gr/Kv/Ep plates. Crushing was induced at a crosshead displacement rate of 0.05 inches per minute for the baseline plates, and at a rate of 0.1 inches per minute for the scaled plates. A 60,000 lb capacity Tinius Olsen universal testing machine was used. Load data were collected at a rate of one scan per second, while displacement data were determined based on a measurement of the time for the crosshead to displace one inch.

3.2 EXPERIMENTAL RESULTS

3.2.1 AS4/3502 Graphite/Epoxy

Typical load-displacement responses of baseline plates and ply-level and sublaminate scaled plates are plotted in Figure 3.5(a) for the steeple trigger mechanism, and in Figure 3.5(b) for the notch trigger mechanism. Note that the load and displacement for the scaled plates have been normalized by the scale factor of 2 to facilitate comparison with baseline plate response. A characteristic "double peak" is seen during the initial loading for the baseline plate with the steeple trigger (Fig. 3.5(a)) but does not appear with the scaled plates, nor with any having notch triggers (Fig. 3.5(b)).

Figures 3.5(a) and 3.5(b) also illustrate the differences in sustained crushing load between the baseline and scaled plates. Sublaminate level scaling appears to yield similar sustained crushing loads as compared to the baseline, however, the ply-level scaled plates have noticeably lower sustained crushing loads relative to the others. This point is more clearly illustrated in Figures 3.6(a) and 3.6(b). Each bar is usually the average of three tests, see Table 1 for details.

Consider first the effect of scale on the peak and sustained crushing loads of plates with steeple trigger mechanisms (Fig. 3.6(a)). Ply-level scaling resulted in peak and sustained crushing loads of 77% and 72%, that of the baseline, respectively. The sublaminate scaled plates had similar peak and sustained crushing loads, which were 101% and 100%, that of the baseline, respectively. Similar comparisons are made among plates having notch trigger mechanisms and are shown in Figure 3.6(b). Ply-level scaled plates having notch triggers performed similar to those with steeple triggers, and peak and sustained crushing loads were 87% and 72%, that of the baseline, respectively. The sublaminate scaled plates exhibited marginally better performance than the baseline with peak and sustained crushing loads of 103% and 106%, respectively. These results would suggest that energy absorption of composite plates is scalable.

Moreover, differences can be observed in the peak to sustained crushing load ratios. Considering again plates with steeple triggers, the ply-level and sublaminate scaled plates had peak to sustained load ratios of 160% and 151%, respectively, compared to the baseline value of 150%. Peak to sustained load ratios for notch triggered ply-level and sublaminate scaled plates were 191% and 153%, respectively, compared to the baseline value of 158%. Table 1 contains a summary of the experimental results.

Another observation from Figures 3.5(a) and 3.5(b) is that regarding load fluctuation. In general, the amplitude of load fluctuation varied between 1000 and 5000 pounds during the sustained crushing phase, with the sublaminate scaled plates tending to the higher end. Correspondingly, from Figures 3.7(a) and 3.7(b), observe that strain built up linearly during the initial compression, before any crushing had begun.

During crushing, strain gage readings fluctuate wildly. This is attributed to load buildup and drop-off as portions of the specimen fragment. With each change from loading to unloading and vice versa, the average strain on each face diverged or converged, respectively. Usually a drop in load signaled the beginning of strain convergence and then sign reversal with continued strain divergence in the new direction. The primary distinction between the two plots is that the sublaminate scaled plate (Fig. 3.7(b)) has a high frequency strain oscillation and "low" strain amplitude, whereas the ply-level scaled plates' (Fig. 3.7(a)) frequency of strain oscillation is lower, while the strain amplitude is slightly higher. The differences in the average strain between Figures 3.7(a) and (b) is attributed to the differences in crushing loads.

3.2.2 AS4/Kevlar-49/3502: Hybrid Graphite-Kevlar/Epoxy

As done for the AS4/3502, the same tests were performed for the hybrid material system AS4/Kevlar-49/3502. A typical load-displacement response of baseline plates as well as ply-level and sublaminate scaled plates is plotted in Figure 3.8(a) for the steeple trigger mechanism, and in Figure 3.8(b) for the notch trigger mechanism. Note that the load and displacement for the scaled plates have been normalized by the scale factor to facilitate comparison with baseline plate response. A characteristic "double peak" is seen during the initial loading for the baseline plate with the steeple trigger (Fig. 3.8(a)), and was also observed for the scaled plates having steeple triggers.

Figures 3.8(a) and 3.8(b) also illustrate the differences in sustained crushing load between the baseline and scaled plates. Sublaminate level scaling appears to yield similar sustained crushing loads as compared to the baseline, however, the ply-level scaled plates have noticeably lower sustained crushing loads relative to the others; this point is more clearly illustrated in Figures 3.9(a) and 3.9(b). Before turning attention to these figures, another observation from Figures 3.8(a) and 3.8(b) is that regarding load fluctuation. In general, the amplitude of load fluctuation varied between 500 and 2000 pounds during the sustained crushing phase, with the sublaminate scaled plates tending to the higher end. This is much less than with the Gr/Ep plates.

Consider first the effect of scale on the peak and sustained crushing loads of plates with steeple trigger mechanisms (Fig. 3.9(a)). Ply-level scaling resulted in peak and sustained crushing loads of 77% and 74%, respectively, that of the baseline. The sublaminate scaled plates had similarly reduced peak and slightly reduced sustained crushing loads, which were 79% and 90%, respectively, that of the baseline. Similar comparisons are made among plates having notch trigger mechanisms and are shown in Figure 3.9(b). Ply-level scaled plates having notch triggers had slightly higher loads than those with steeple triggers, and peak and sustained crushing loads were 87% and 76%, respectively, that of the baseline. The sublaminate scaled plates performed comparably to the baseline with peak and sustained crushing loads of 95% and 92%, respectively. Moreover, differences can be observed in the peak to sustained crushing load ratios. Table 1 summarizes the experimental results.

Again, considering plates with steeple triggers (Fig. 3.9(a)), the ply-level and sublaminate scaled plates had peak to sustained load ratios of 173% and 146%, respectively, compared to the baselines 167%. Peak to sustained load ratios for notch triggered ply-level and sublaminate scaled plates (Fig. 3.9(b)) were 208% and 187%, respectively, compared to the baseline's 181%.

3.2.3 Comparison between the AS4/3502 and AS4/Kevlar-49/3502

The crushing response of the two material systems are compared here. First, comparisons are made between the two material systems using typical load-displacement plots. Figures 3.10 show baseline plates, Figures 3.11 show ply-level scaled plates, and Figures 3.12 show sublaminate scaled plates. Figures 3.10(a), 3.11(a), and 3.12(a) compare plates with steeple triggers, and Figures 3.10(b), 3.11(b), and 3.12(b) compare plates with notch triggers. Overall, there appears to be higher load fluctuation amplitude and frequency for the Gr/Ep as compared to the Gr/Kv/Ep, that is, the plots show larger spikes occurring in greater numbers, as evidenced in Figures 3.10, 3.11, and 3.12. Continuing to compare the "noisiness" of the various plots, compare Figures 3.11 with Figures 3.12 and restrict the attention to only Gr/Ep. The plots for Gr/Ep in Figures 3.11 are for ply-level scaled plates and are less noisy, or flatter, than those in Figures 3.12 for the sublaminate scaled plates. Now compare the same figures but restrict attention to the Gr/Kv/Ep plots; it is again evident that the ply-level scaled plates' crushing response is less noisy and flatter than that of the sublaminate scaled plates. Now focus on the bar charts of Figures 3.13 and 3.14 comparing peak and sustained crushing loads of Gr/Ep and Gr/Kv/Ep.

From Figures 3.13 the Gr/Ep appears to have only marginally higher peak loads relative to the Gr/Kv/Ep; the only noteworthy difference is in Figure 3.13(a) where for sublaminate scaled plates the Gr/Ep is 114% that of Gr/Kv/Ep. There are greater differences in the sustained crushing loads, as illustrated in Figures 3.14. The sustained load carried by the Gr/Ep for sublaminate scaled plates with steeple (a) and notch triggers (b) is 124% and 140%, respectively, that of Gr/Kv/Ep. For ply-level scaled plates the difference is less with Gr/Ep being 108% and 115% of that of Gr/Kv/Ep with steeple and notch triggers, respectively, and 110% and 122% for baseline plates.

4. DISCUSSION OF RESULTS

4.1 TEST FIXTURE PERFORMANCE

A flat plate crush test fixture was designed to give a long crush stroke, and to be simple to use. The fixture was used to study two material systems and gave consistent, repeatable results. Though the fixture performed as intended, once built, field testing revealed where further improvements could be made. The following list are a few of the changes that can increase flexibility and ease of use of the new fixture.

1. Increase the maximum gap between the knife edges to accommodate thicker specimens. The easiest approach is to machine away material from the flat side of the knife edges.

2. Variable thickness plates can be accommodated in the current design by using shims behind the knife edges, but this is inconvenient. A simple change is to add a column of regularly spaced set screws along the length of the support posts to push the knife edges out of the keyway and into contact with the composite plate.

3. The support posts were not hardened because there was concern that the asymmetry introduced by the addition of the keyway would unbalance the residual stress which could warp the posts during a heat treatment. Unfortunately, when the posts are driven out of the base plate after a test the enormous friction created by the wedge action of the crushed composite plate tends to scratch and gall the post as it slides past the base plate. This damage makes it difficult to insert the post for the next test.

4. A more likely trigger mechanism to initiate crushing in a real structure might be the J-trigger mechanism rather than the machined-in types employed here. The J-trigger is a molded-in curl at the end of a composite plate that is intended to fracture upon impact and thus initiate crushing at that location. This trigger mechanism is currently under investigation by the supporters of this research. There is enough space between the support posts to accommodate plates with the J-trigger mechanism. The modification could be accomplished by simply installing pins in one pair of the support posts on the J-trigger side to act as blocks to prevent the knife edges from sliding down, and locating them just far enough up from the base plate to clear the J-trigger.

4.2 OBSERVATIONS ON CRUSHING BEHAVIOR

4.2.1 Effect of Trigger Mechanism on Peak and Sustained Crushing Loads

Specimens having a steeple trigger tended to delaminate across the width abruptly because crushed material at the tip formed a divisive wedge. This mechanism inhibits progressive fracture and crushing of the 0° plies by encouraging them to spread outward. This effect was manifested initially by a "double peak" and was observed only in plates with steeple triggers, which included the baseline, ply-level, and sublaminate scaled Gr/Kv/Ep plates, and baseline Gr/Ep plates. The first peak of the "double peak" is sudden, large scale delamination along the width of the plate, and the second is fiber fracture. The notch triggered plates had a higher peak load precisely because there was no wedge type mechanism forcing delamination. For this study, then, the most important variable affecting the magnitude of the sustained crushing load is the scaling method.

The trigger mechanism also appears to play a small role in the magnitude of the sustained crushing load. Among plates scaled identically, those with the steeple trigger mechanism had a consistently lower sustained crushing load than those with notch triggers. This would suggest that a less efficient crushing mode was induced initially and persisted throughout the test.

4.2.2 Effect of Scale on Peak and Sustained Crushing Loads

The data clearly show that to avoid a reduction in SSCS when scaling up from the baseline, sublaminate level scaling is superior to ply-level scaling. Inspection of the remnants of crushed plates reveals why. The 0° plies in the ply-level scaled plate are grouped together in two bunches, and on crushing the bulk of them splay outward and remain largely intact, contributing little to energy absorption. For sublaminate scaled plates the 0° plies are dispersed into four groups. The effect is to move more 0's toward the mid plane where they are better constrained by the 45's and hence crush more completely. The reduction in the number of 0's near the outside leaves fewer to splay outward without crushing. Finally, the divisiveness of the wedge created by the mid plane 45's is reduced because some of their numbers are moved outward. Farley [3] found that increasing the number, n, of 0's grouped together in tubes of the stacking sequence, $[\pm 45^{K}/0_{n}{}^{Gr}]_{S}$, (K is

Kevlar, and Gr is graphite) did not result in an increase in SSCS, but a decrease with transition from a brittle fracturing crushing mode to the lamina bending crushing mode. Farley showed that increasing the number of 0's grouped together increased the compliance of the laminae bundles causing the change in crushing mode. He further suggested that for larger n it is necessary to intersperse the 0's throughout the stacking sequence. The sublaminate scaled plates have this interspersing relative to the ply-level scaled plates and in fact do crush in the more efficient mode. The mechanisms governing crushing mode would appear to be operating in both the flat plate test and tube tests.

4.2.3 Plate Energy Absorption and More Complex Structures

The lateral support to the plate provided by the posts is giving load-displacement behavior similar to the behavior of the self-supporting structural shapes, such as tubes. Though the plots are similar for both flat plates and tubes, and crushing and not global buckling is occurring in both cases, it is not certain that the supported plates are failing by entirely the same mechanisms as the self supporting tubes. The opportunity exists to look for correlation between energy absorbed in the crushing of flat plates and more complex structural shapes (tubes) by comparing to work performed by Farley [3] and Hamada [7]. Farley tested a variety of graphite and Kevlar reinforced epoxy tubes and measured SSCS was in the range of about 50 to 100 Nm/g. Energy absorption of flat plates in this study ranged between 41 and 72 Nm/g which is similar to Farley's results. Hamada measured the energy absorption for ±0° AS4 graphite/PEEK thermoplastic tubes to be about 180 Nm/g. The test fixture should then be expected to yield similarly spectacular increases in SSCS when plates having a PEEK thermoplastic matrix but the same fiber architecture as used in this study are tested. There seems to be reasonable correlation between the flat plate and tube tests, but the following discussion suggests the differences may be important.

In the self-supporting structures, such as rectangular tube-stiffened beams, we can imagine that the intersection of web with the flat walls of the square tube act to prevent buckling analogous to the way the posts support flat plates. If we consider the rectangular tube alone, each wall of the tube is supported by the integral connection it has with the edge of the adjacent wall. Upon crushing, the sides of the square tube broom outward, placing the off-axis fibers at the root of the split in tension. In contrast, the flat plate experiences compression in the thickness direction from the reaction offered by the support posts once crushing has begun. This compression would provide the friction needed to prevent the delaminated off-axis laminae from pulling out from under the knife edged supports, thus providing the mechanism needed for the material to resist splaying into the open space between the support posts on each side. These different methods of support appear to induce similar failure mechanisms, but also may be why the Gr/Ep plates had higher SSCS's than comparable hybrid Gr-Kv/Ep plates, a different result from that obtained with tubes.

These differences may affect our ability to predict the crushing behavior of the more complex structural shapes. Recall that for this study the chamfer trigger was eliminated because no peak load was observed in the previous study [5]. This difference between tube and plate test methods should serve as a warning because the chamfer is a routinely used trigger for tubes and gave satisfactory peak-to-sustained load ratios. This test fixture for crushing plates appears to be performing well, and should serve as an efficient, cost effective screening test for candidate material systems. To establish the flat plate test method as an alternative to building expensive, difficult-to-fabricate structural elements, different material systems should be tested in plate and structural forms to assess the degree of correlation that exists between the tests.

5. CONCLUDING REMARKS

A flat plate specimen crush test fixture for measuring energy absorption from an earlier study, Jackson *et al.* [5], was redesigned and fabricated to eliminate the problem of binding of the load transfer platen with the guide posts. Further modifications were to increase the stroke, and combine the two test fixtures into one. This new crush test fixture was shown to produce load-displacement histories exhibiting well developed sustained crushing loads over long strokes. An experimental study was conducted on two material systems: AS4/3502 graphite/epoxy, and a hybrid AS4-Kevlar/3502 composite. The effect of geometric scaling of specimen size, the effect of ply-level and sublaminate-level scaling of the stacking sequence of the full scale specimens, and the effect of trigger mechanism on the energy absorption capability was investigated.

The new crush test fixture and flat plate specimens produced peak and sustained crushing loads that were lower than obtained with the old crush test fixture because the geometry of support was altered giving less support. The trigger mechanism used influenced the specific sustained crushing stress (SSCS), with the steeple trigger yielding lower values than the notch trigger. The results of this study indicated that to avoid any reduction in the SSCS when scaling from the 1/2 scale to full scale specimen size, the sublaminate-level scaling approach should be used, in agreement with experiments on tubes. The use of Kevlar in place of the graphite 45° plies was not as effective a means for supporting and containing the 0° graphite plies and resulted in a drop in the SSCS. This result for plates did not correlate with the result obtained using tubes. Future work should focus on determining where the test results for plates and the more complex structural shapes differ before the test can be recommended for general use. Rate effects, and thermoplastic matrix systems are other areas for investigation.

6. REFERENCES

1. 'Light Fixed- and Rotary-Wing Aircraft Crashworthiness,' MIL-STD-1290 (AV), January 1974.

2. Och, F., "Helicopter Crashworthiness-Problems and Promises," International Conference and Exposition on Structural Impact and Crashworthiness, Imperial College, London, United Kingdom, July 16-20, 1984.

3. Farley, G.L., "Energy-Absorption Capability of Composite Tubes and Beams," Ph.D. dissertation, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, May 1989.

4. Jones, L.E., and Carden, H.D., "Evaluation of Energy Absorption of New Concepts of Aircraft Composite Subfloor Intersections," NASA TM 2951, November 1989.

5. Jackson, K., Morton, J., Traffanstedt, C., and Boitnott, R., "Scaling of Energy Absorbing Composite Plates," *American Helicopter Society*, 48th Annual Forum, Washington, D.C., June 3-5, 1992.

6. Hanagud, S., Craig, J.I., Sriram, P., and Zhou, W., "Energy Absorption Behavior of Graphite Epoxy Composite Sine Webs," *Journal of Composite Materials*, 448-459, vol. 23, no. 5, May 1989.

7. Hamada, H., Coppola, J.C., Hull, D., Maekawa, Z., and Sato, H., "Comparison of Energy Absorption of Carbon/Epoxy and Carbon/PEEK Composite Tubes," *Composites*, 245-251, vol.23, no. 4, July 1992.

8. Morton, J., "Scaling of Impact Loaded Carbon Fiber Composites," *AIAA Journal*, 989-994, 26, 8, August 1988.

9. Kellas, S., and Morton, J., "Strength Scaling in Fiber Composites," NASA Contractor Report 4335, November 1990.

Table 1. Summary of Experimental Data

TRIGGER MECHANISM	No. of Tests	PEAK LOAD (lb)	AVG. CRUSHING LOAD (lb)	SSCS (Nm/g)
AS4/3502				
Steeple Baseline	4	3474	2309	62.9
Steeple Ply-level	3	2675*	1665*	43.3
Steeple Sublam.	3	3515*	2327*	60.5
Notch Baseline	5	4133	2623	71.5
Notch Ply-level	3	3600*	1885*	49.0
Notch Sublam.	3	4253*	2774*	72.1
AS4/Kevlar-49/3502				
Steeple Baseline	3	3467	2092	53.7
Steeple Ply-level	2	2655*	1538*	40.9
Steeple Sublam.	3	2756*	1880*	49.9
Notch Baseline	2	3900	2155	55.3
Notch Ply-level	2	3398*	1633*	43.4
Notch Sublam.	4	3720*	1986*	52.7

*load values are scaled (actual loads have been divided by the scaling factor 4)

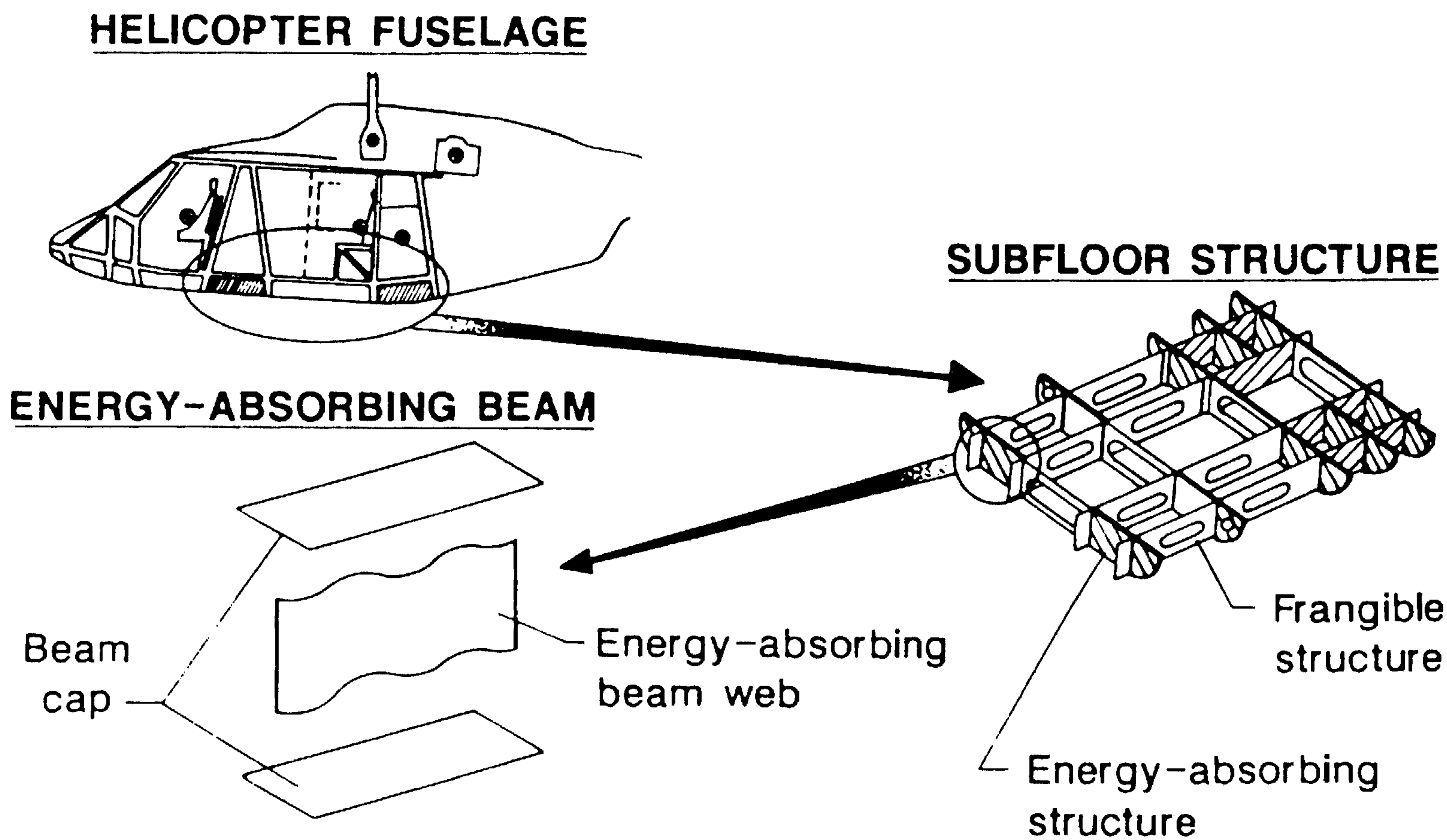


Figure 1.1 Energy absorbing helicopter subfloor structure, ref. [3].

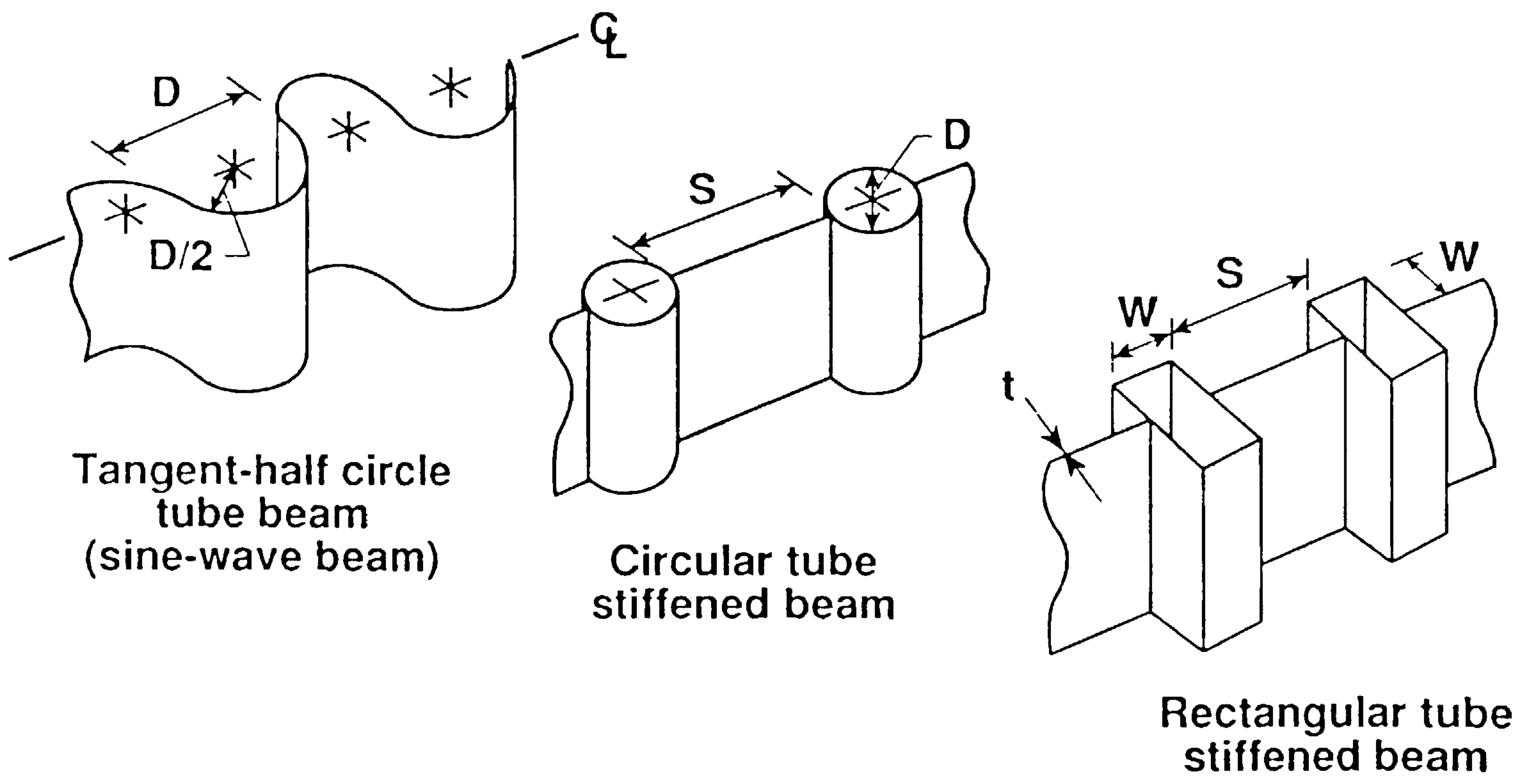


Figure 1.2 Energy absorbing beam concepts, ref. [3].

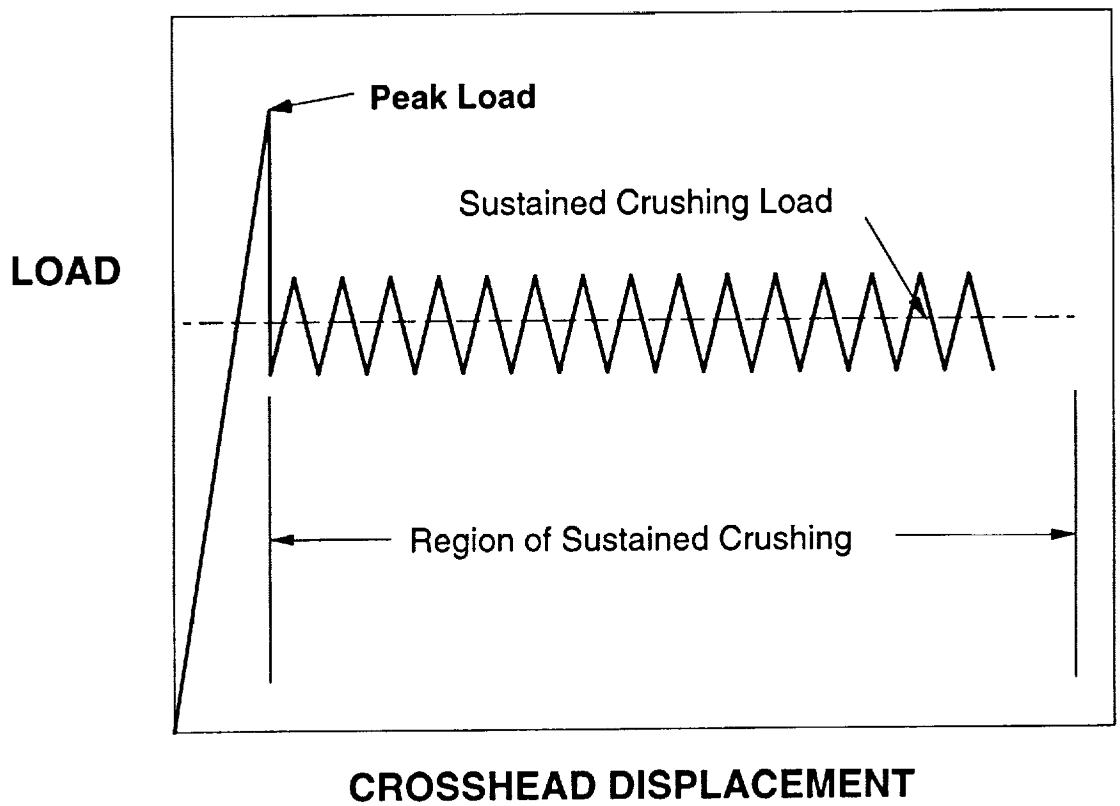


Figure 1.3 Idealized load verses displacement response for crushing of a composite cylinder.

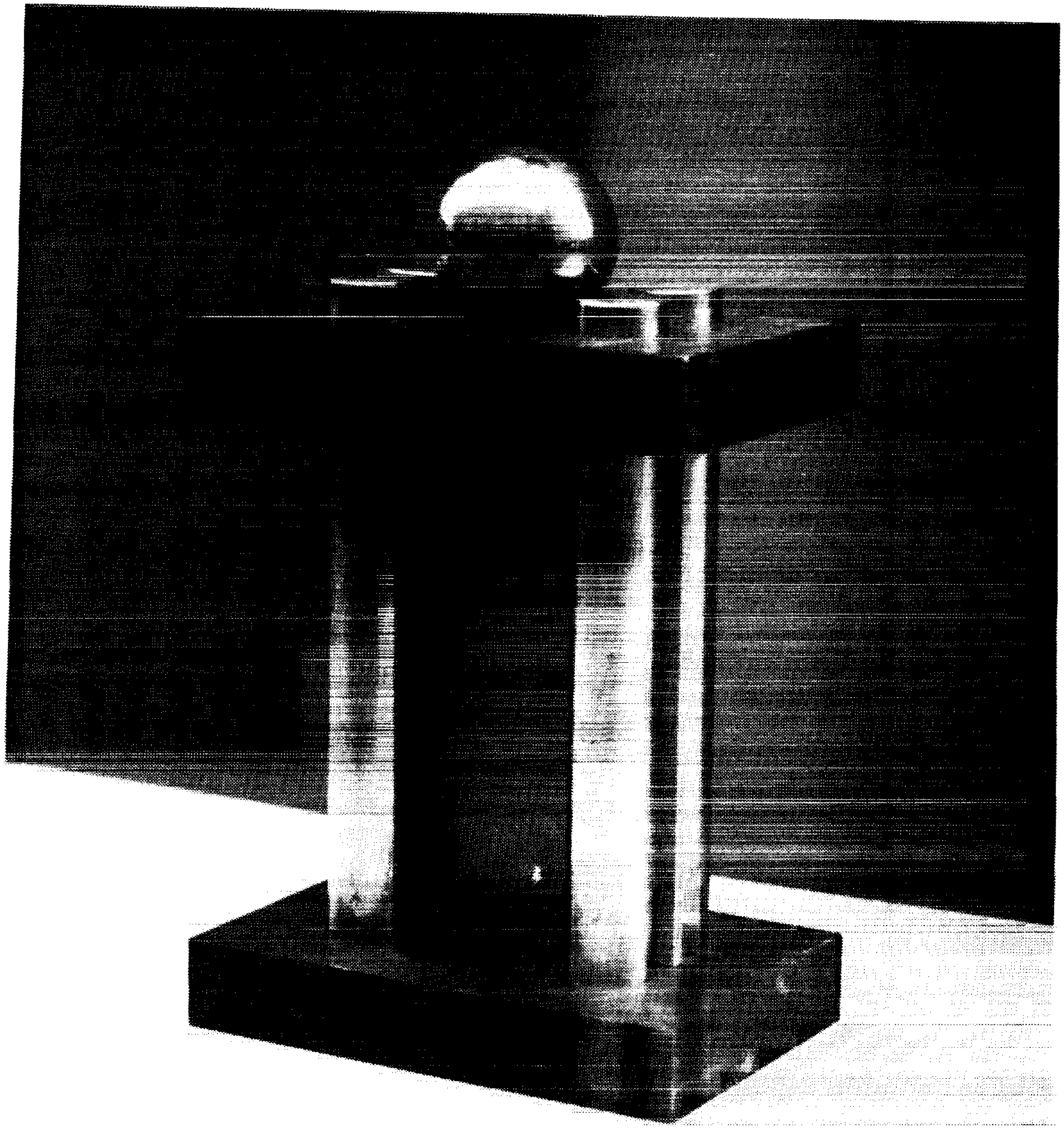


Figure 2.1 First generation crush test fixture, photograph taken of fixture from reference [5].

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

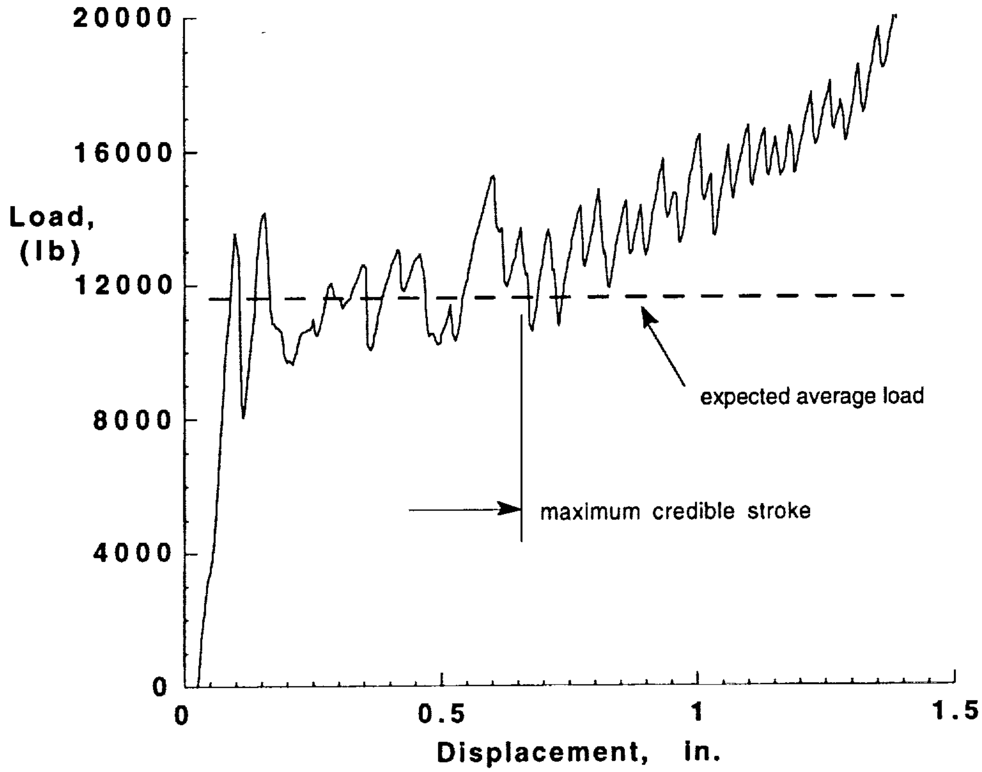


Figure 2.2 Typical crushing response of a composite plate specimen in the first generation crush test fixture. Note the runaway rise in load, indicative of binding within the test fixture (test data from C. Traffanstedt's masters thesis, VPI&SU, Blacksburg, VA, expected 1993).

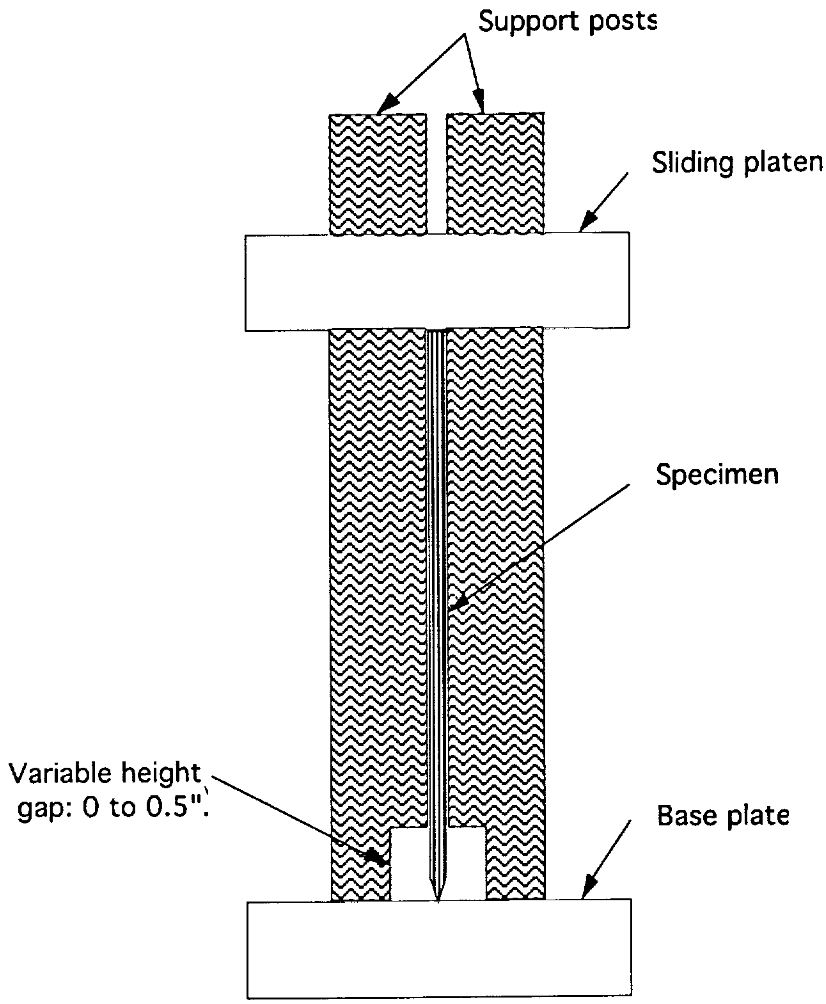


Figure 2.3 Sideview of the baseline model of the first generation test fixture with a cutout machined into the plate support posts. Purpose was to provide an adjustable size gap for debris to accumulate in.

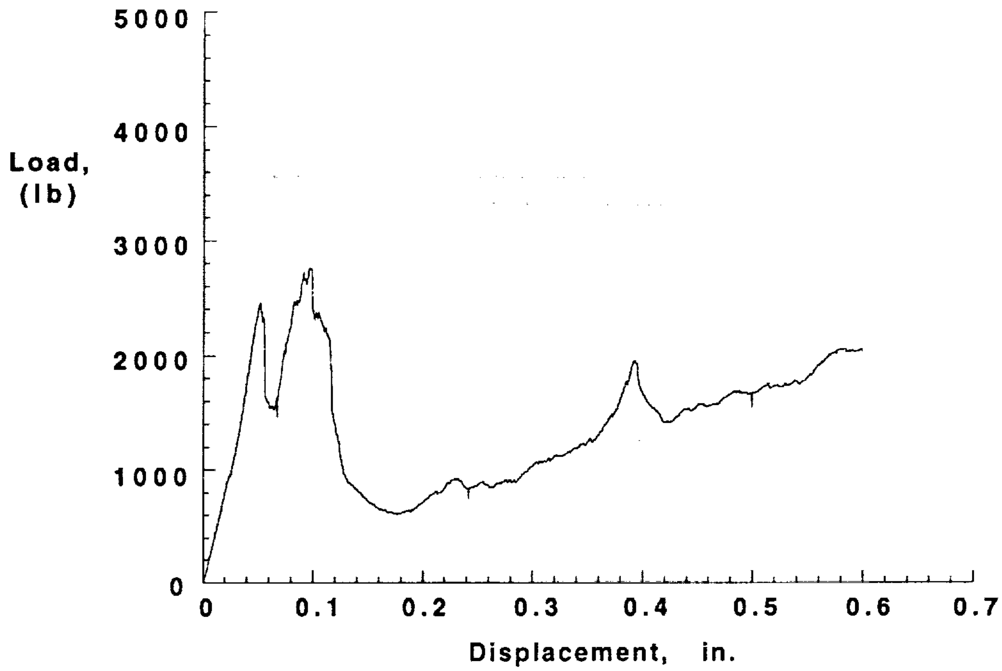


Figure 2.4 Crushing response of a composite plate in the old crush fixture, but with 3/16" of the plate unsupported.

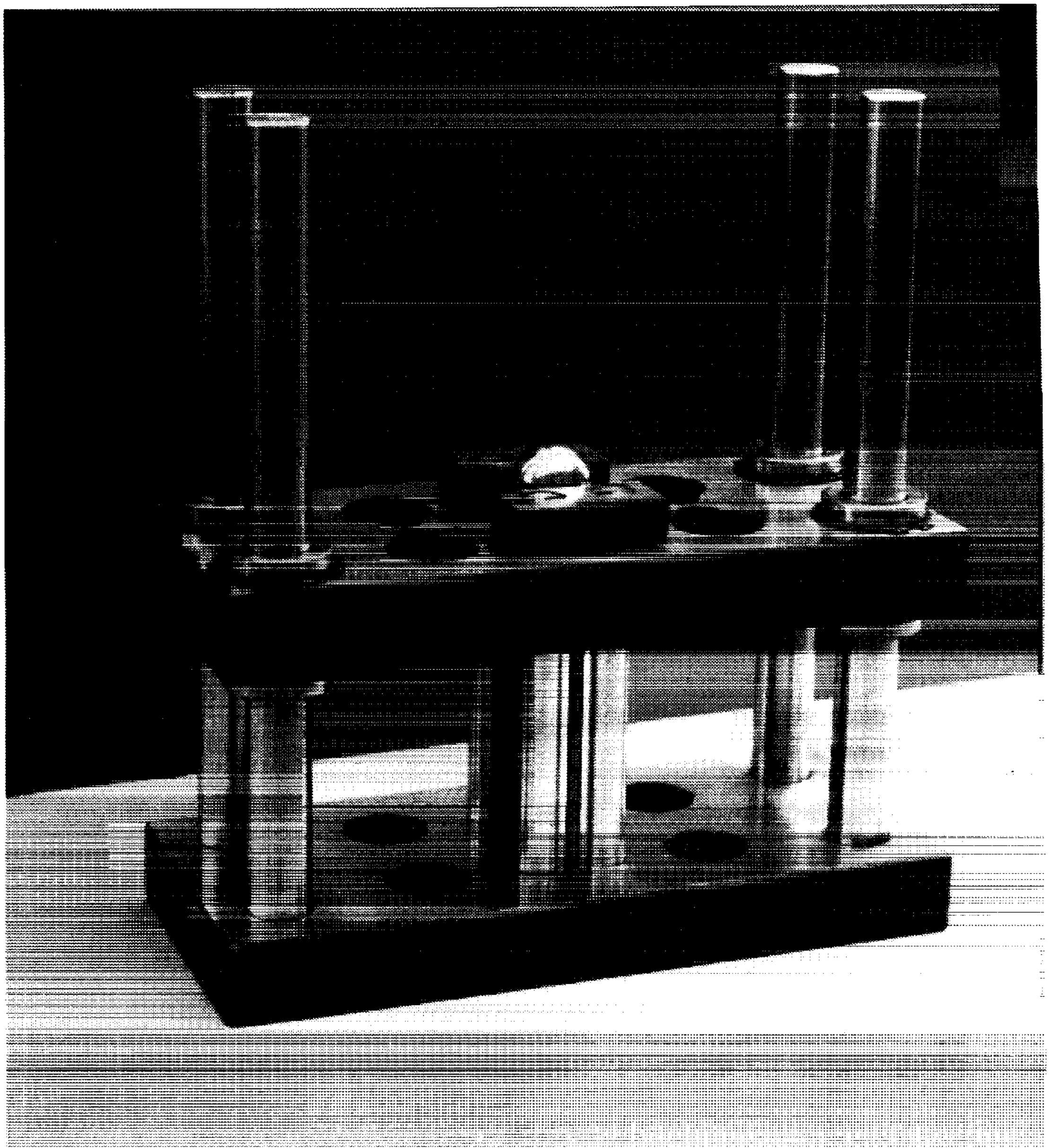


Figure 2.5 New test fixture configured for baseline or 1/2 scale specimens.

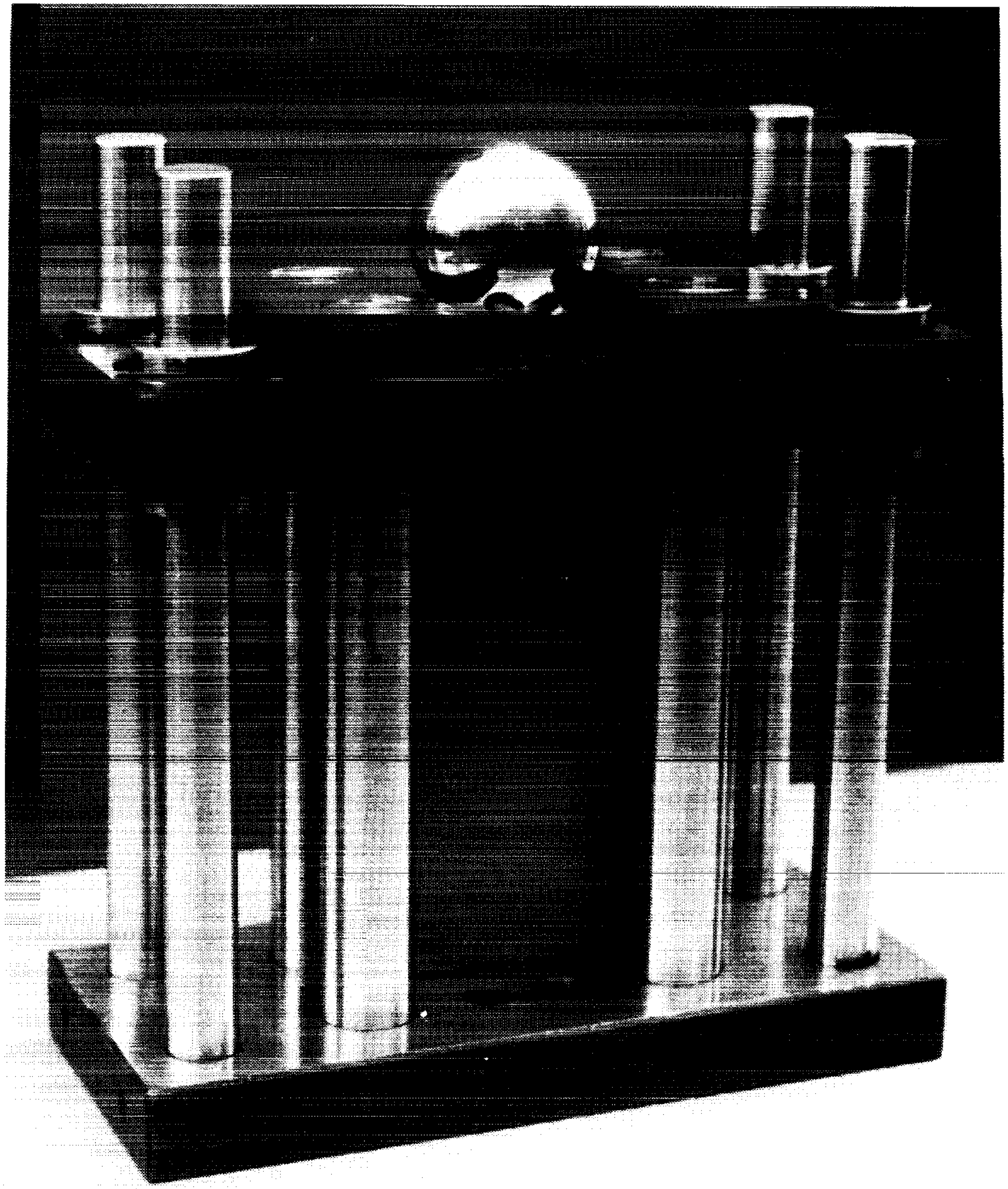


Figure 2.6 New test fixture configured for full scale specimens.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

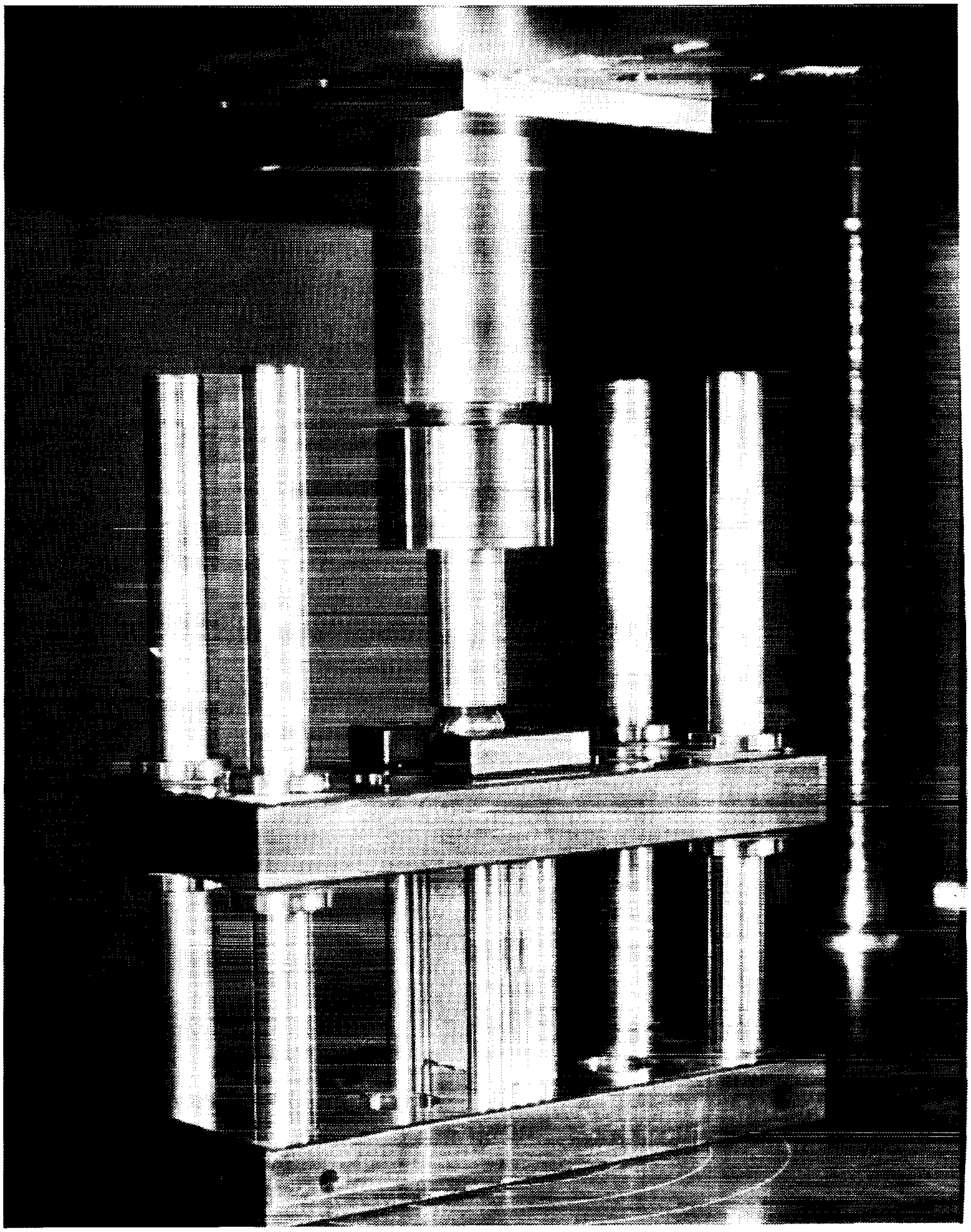


Figure 2.7 Baseline-configured test fixture with loading rod and diameter-reduction adapter attached.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

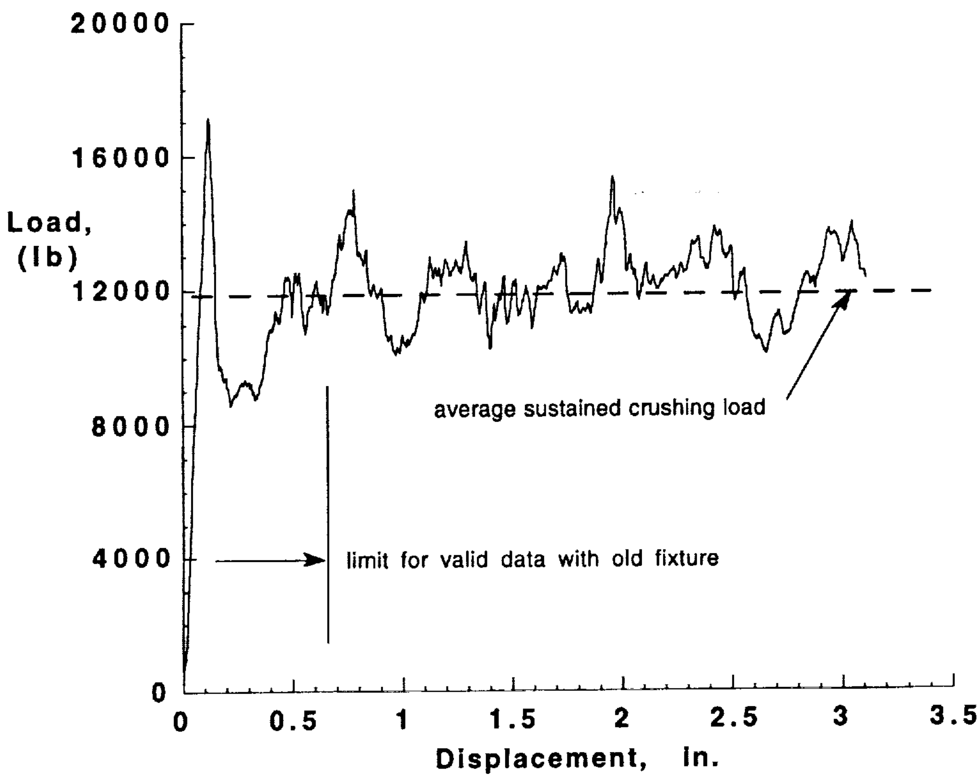


Figure 2.8 Typical crushing response of a composite plate specimen in the new crush test fixture. Note the steady sustained crushing load and long stroke.

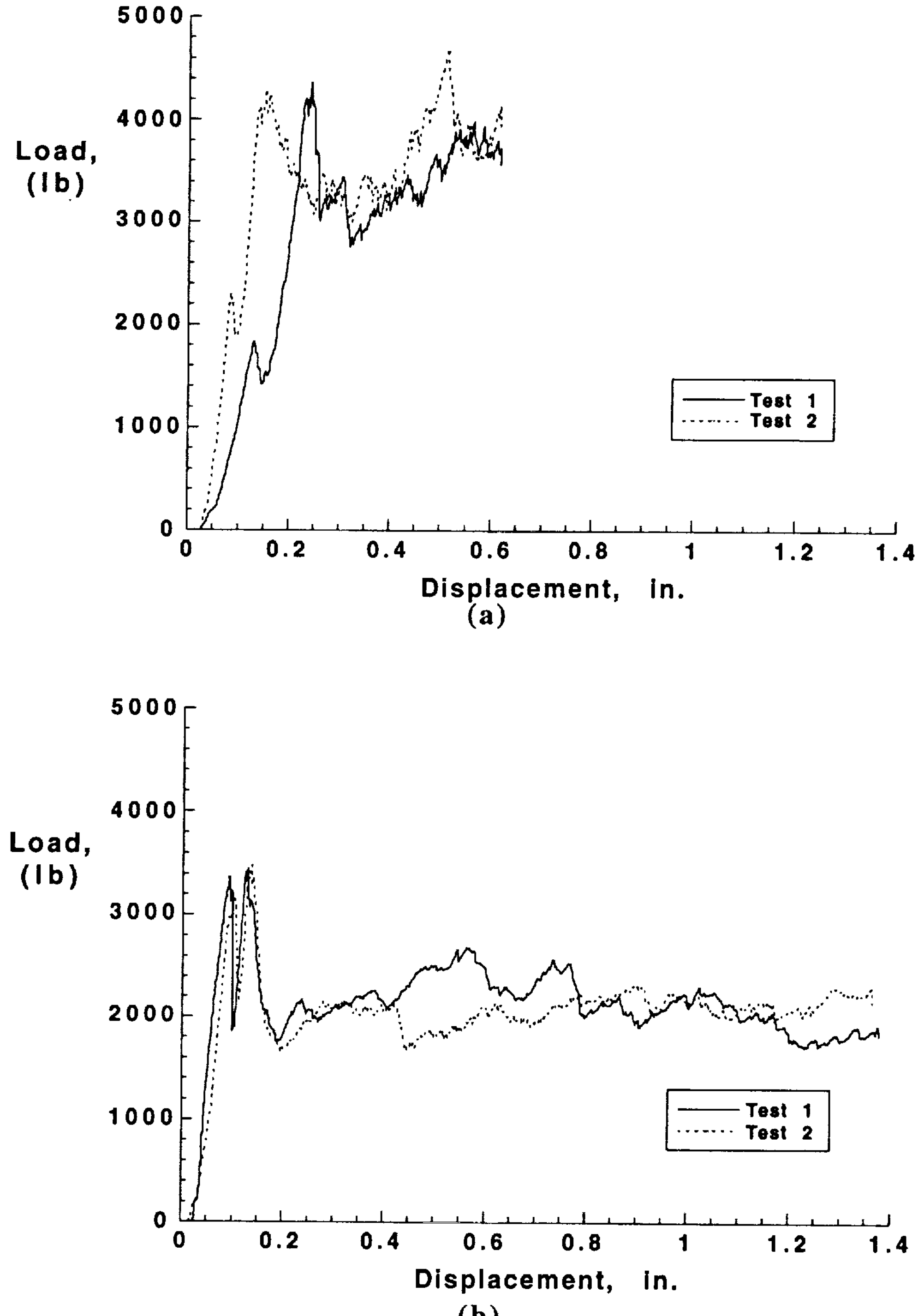


Figure 2.9 Crushing response of baseline Gr-Kv/Epoxy plates with steeple trigger mechanism in the (a) old fixture and (b) new fixture.

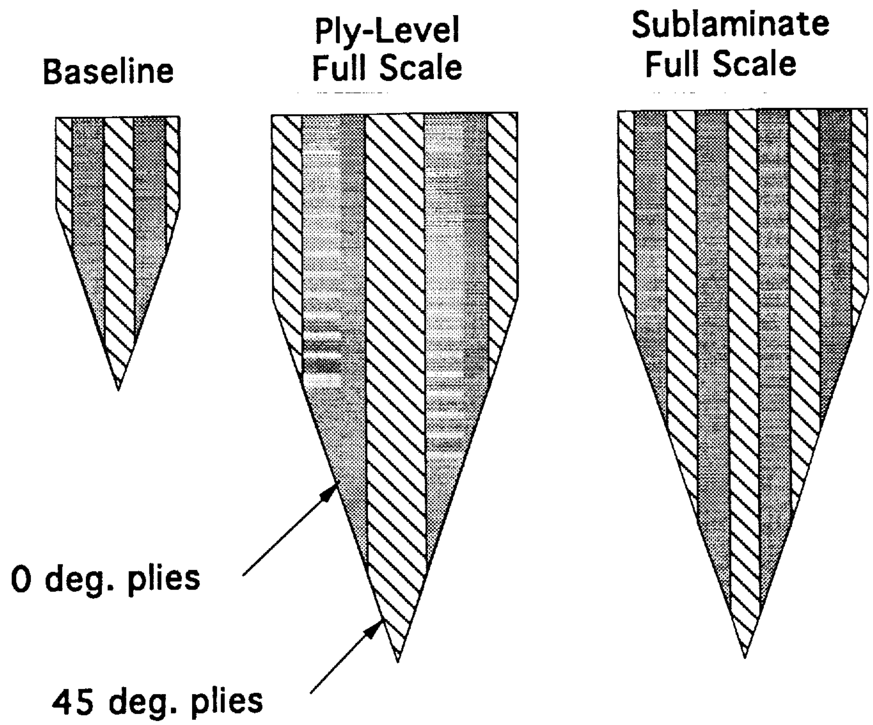


Figure 3.1 Schematic of baseline, ply-level, and sublaminate-level scaled plates in cross-section (steeple trigger shown).

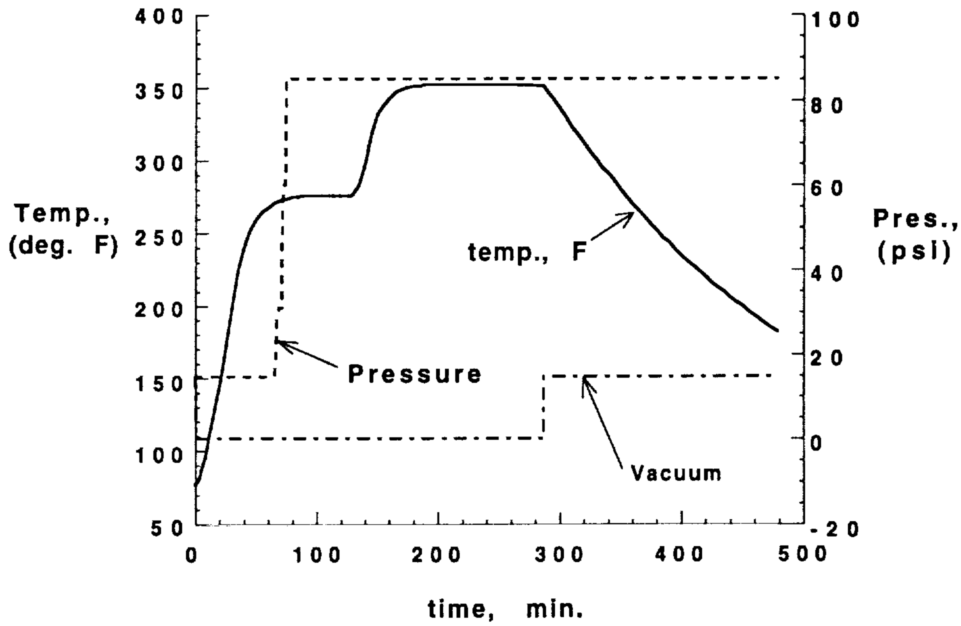


Figure 3.2 Typical laminate cure cycle.

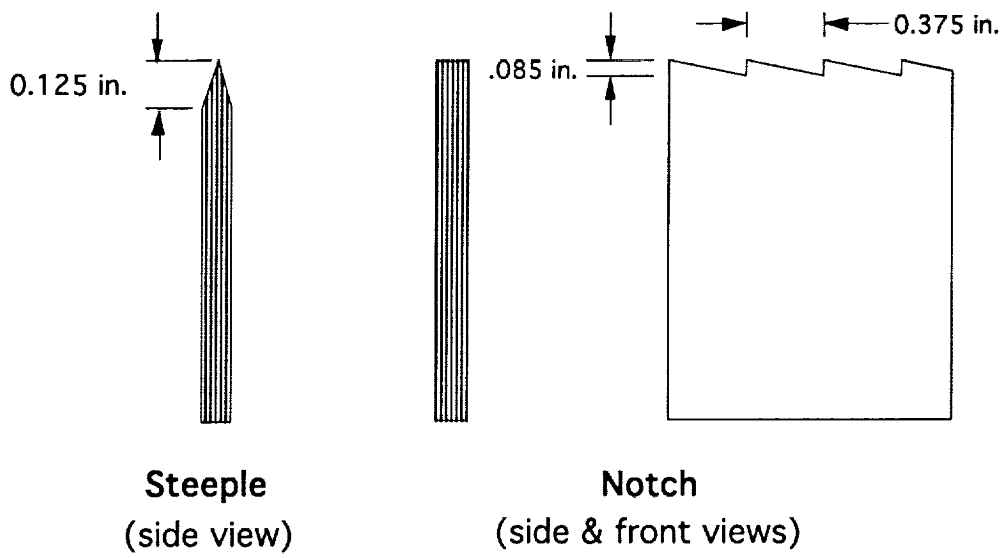


Figure 3.3 Schematics of trigger mechanism used in the baseline specimens (triggers for full scale specimens are doubled in dimension).

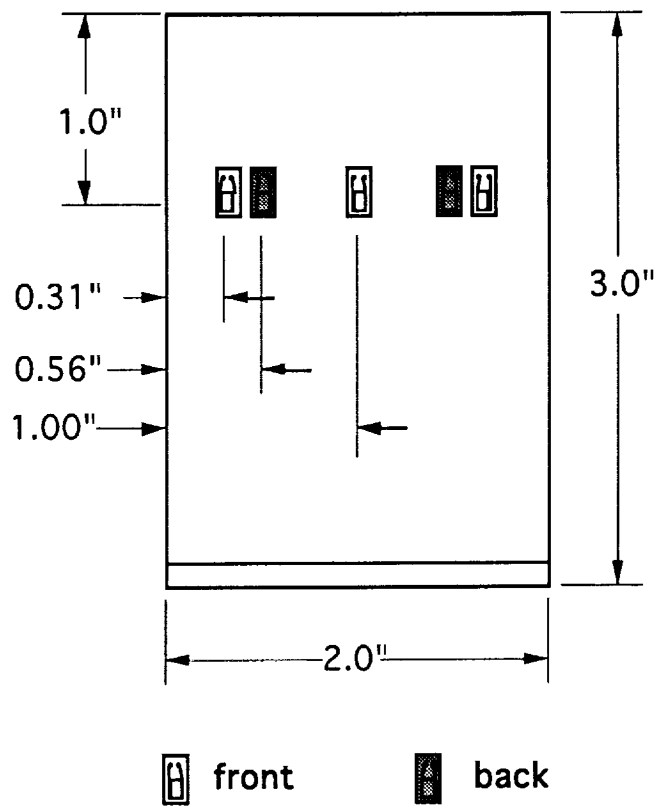
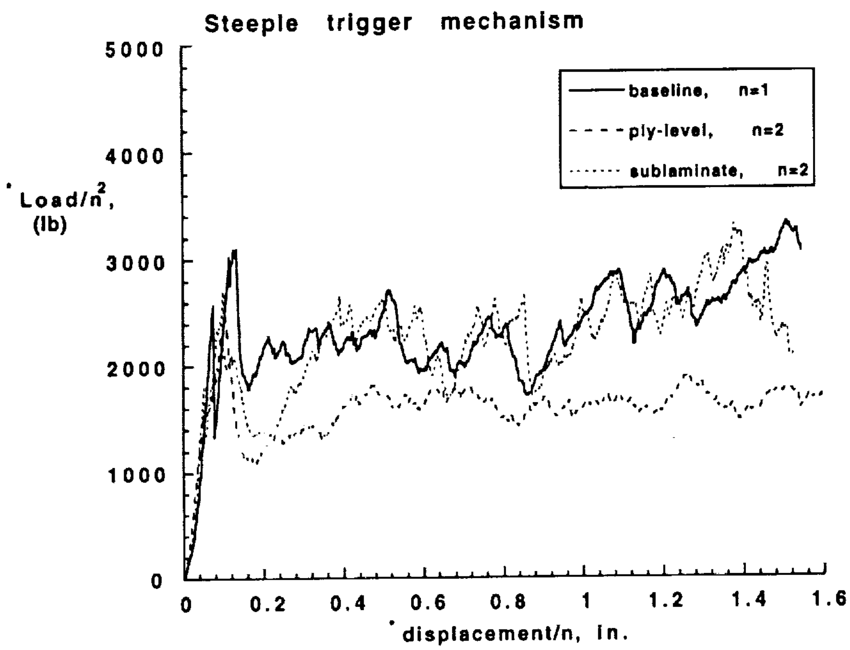
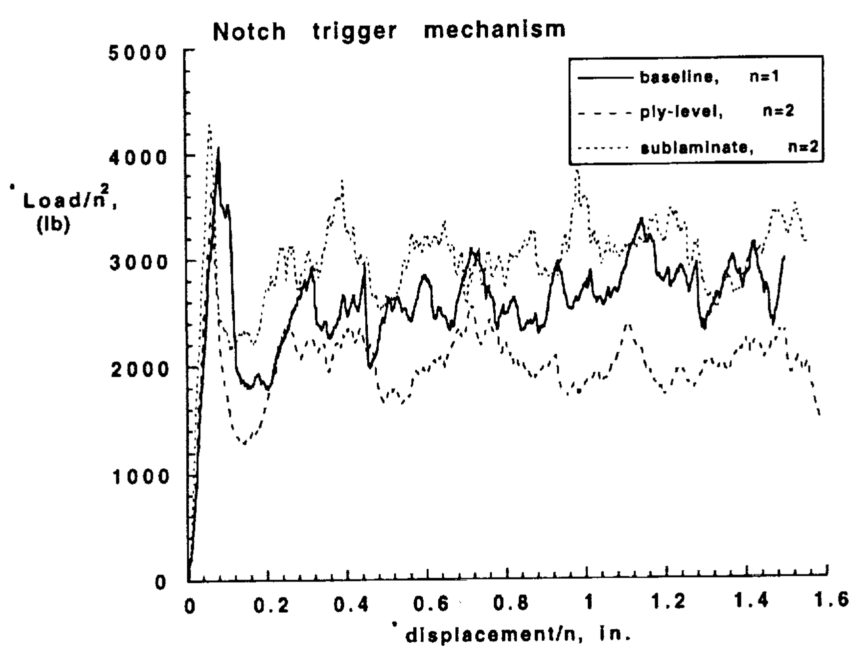


Figure 3.4 Strain gage placement on the baseline plate.

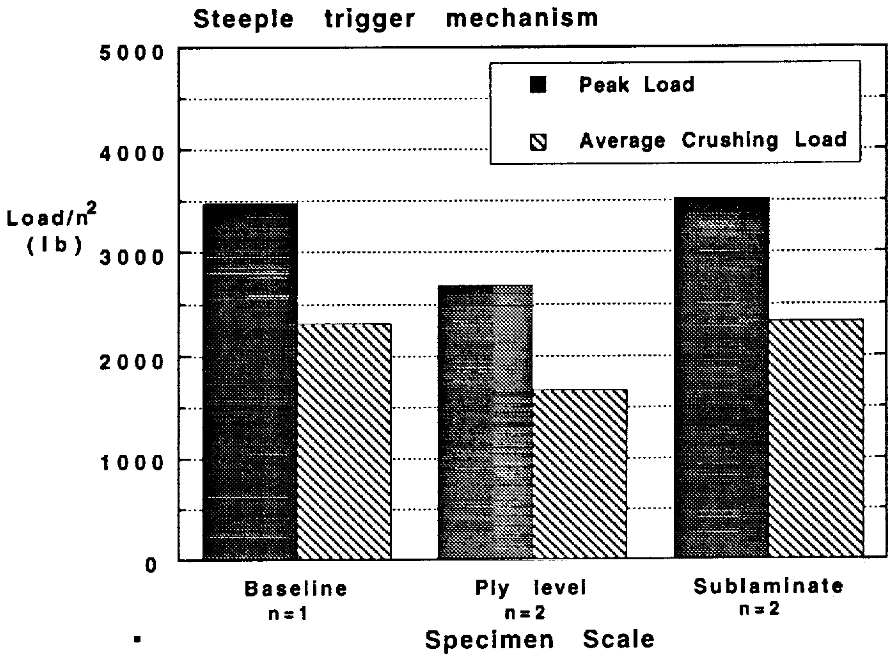


(a)

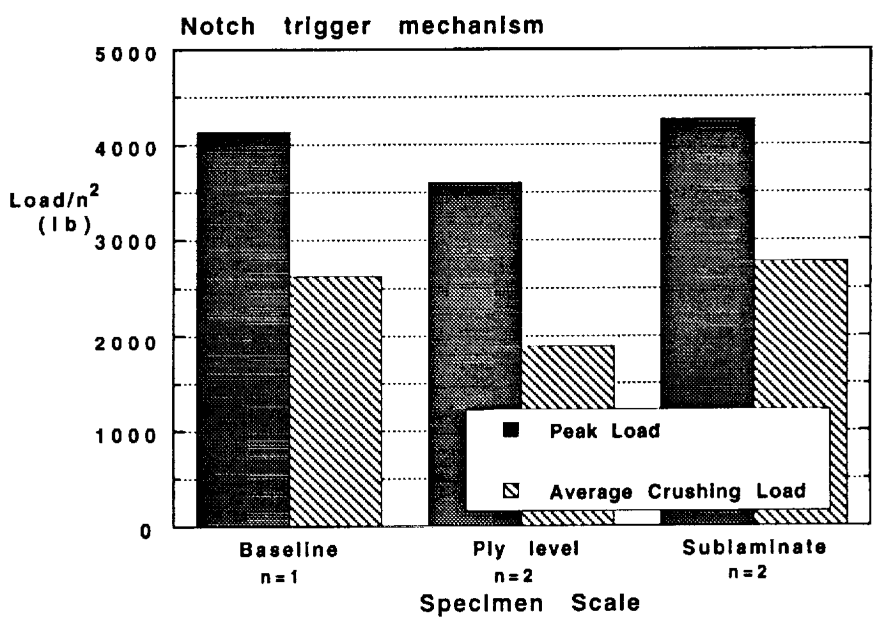


(b)

Figure 3.5 Effect of scaling on crushing response of baseline, sublaminate-, and ply-level scaled AS4/3502 plates with (a) steeple and (b) notch triggers. *Loads and displacements have been scaled.



(a)



(b)

Figure 3.6 Summary of crushing data: AS4/3502 with **(a)** steeple trigger mechanism and **(b)** notch trigger mechanism.

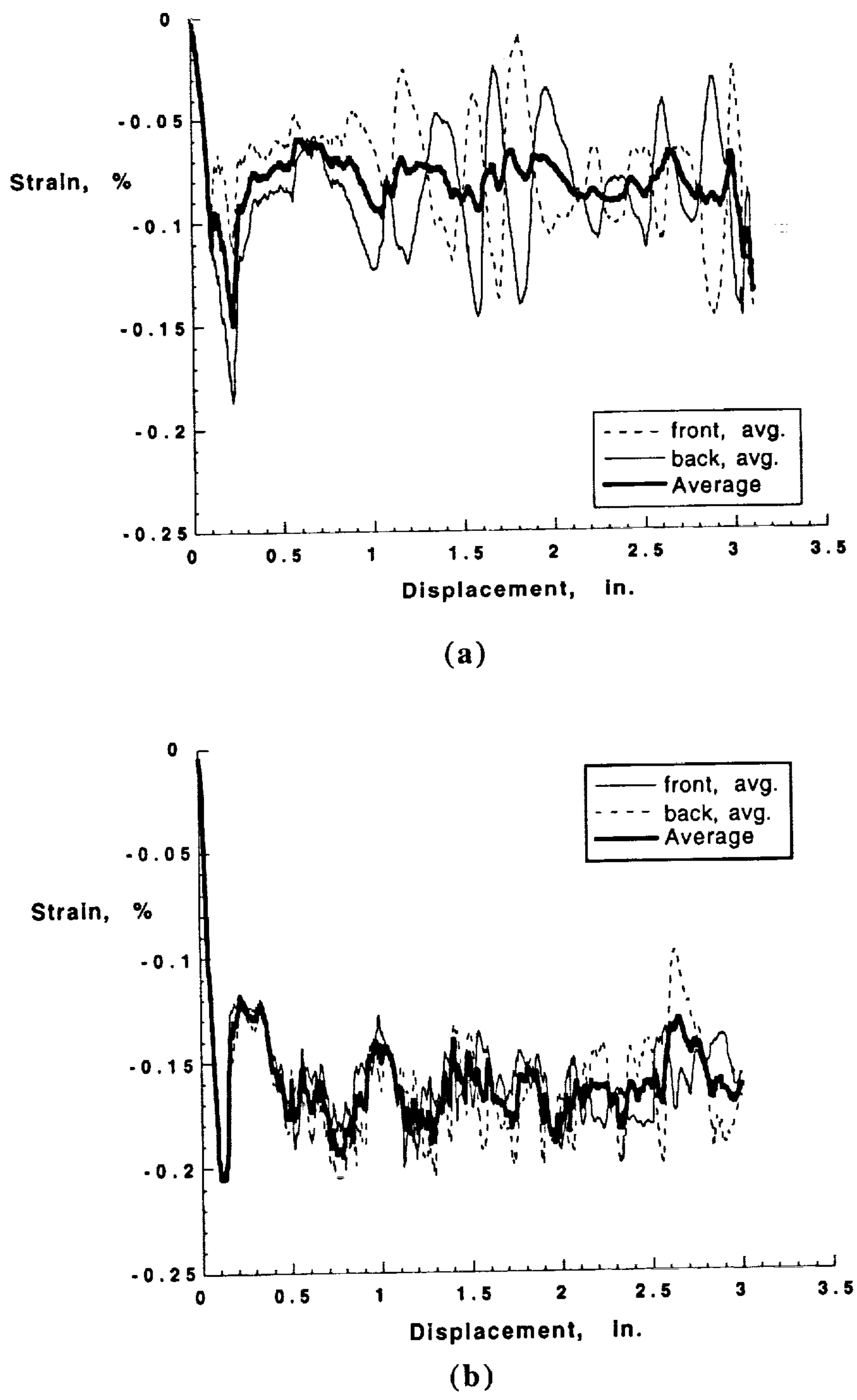
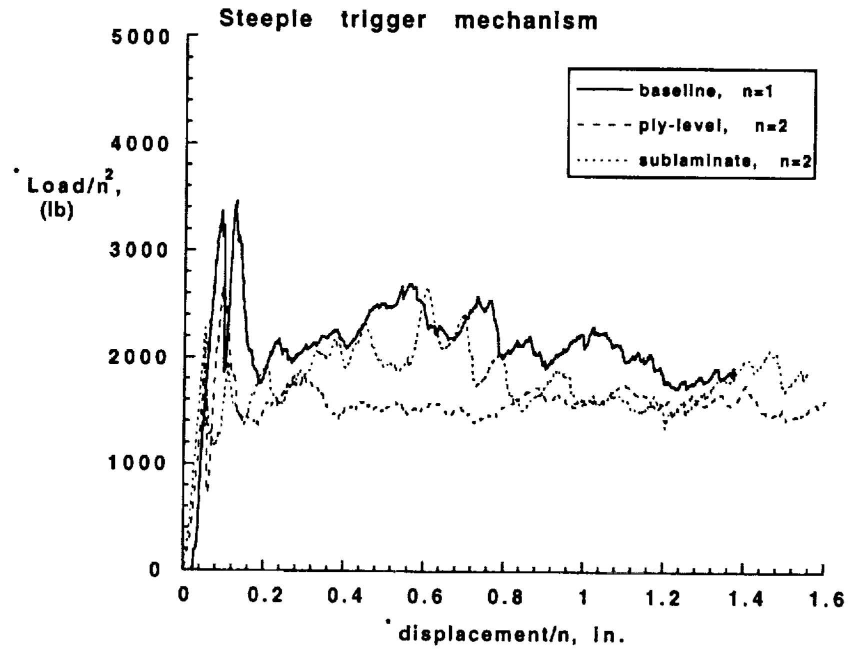
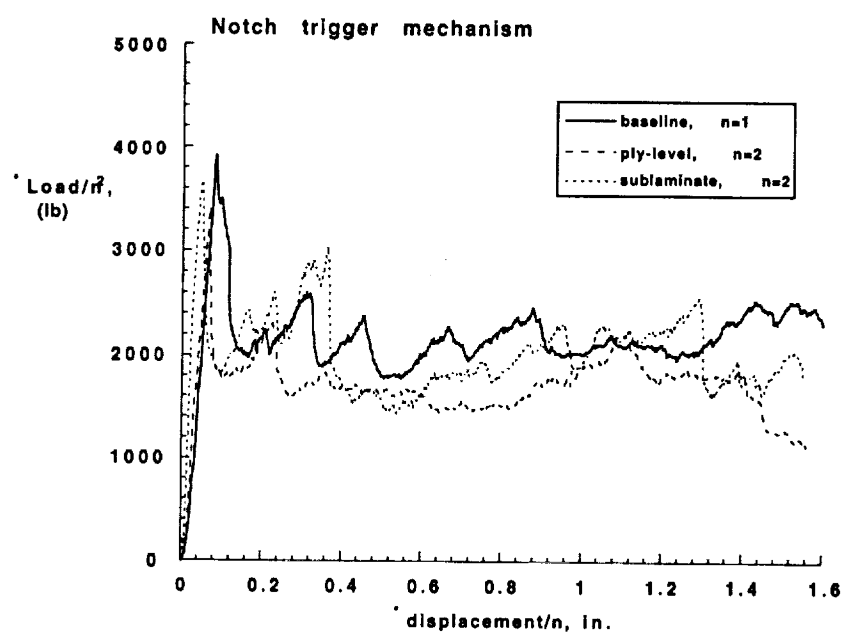


Figure 3.7 Typical strain vs. displacement response of (a) ply-level scaled and (b) sublaminate-scaled AS4/3502 with steeple trigger mechanism.

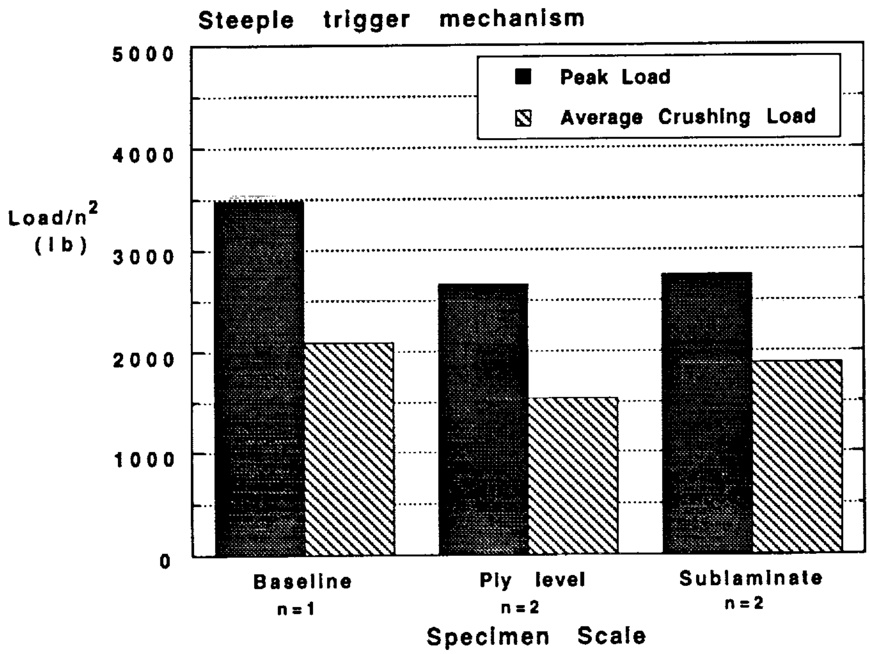


(a)

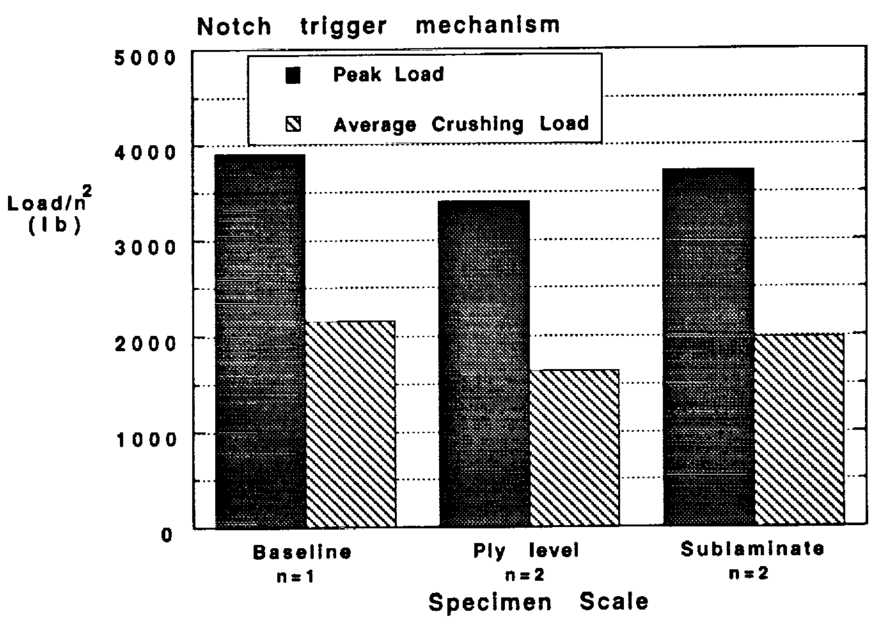


(b)

Figure 3.8 Effect of scaling on crushing response of baseline, sublaminate-scaled, and ply-level-scaled AS4/Kevlar/3502 plates with (a) steeple triggers and (b) notch triggers. *Loads and displacements have been scaled.

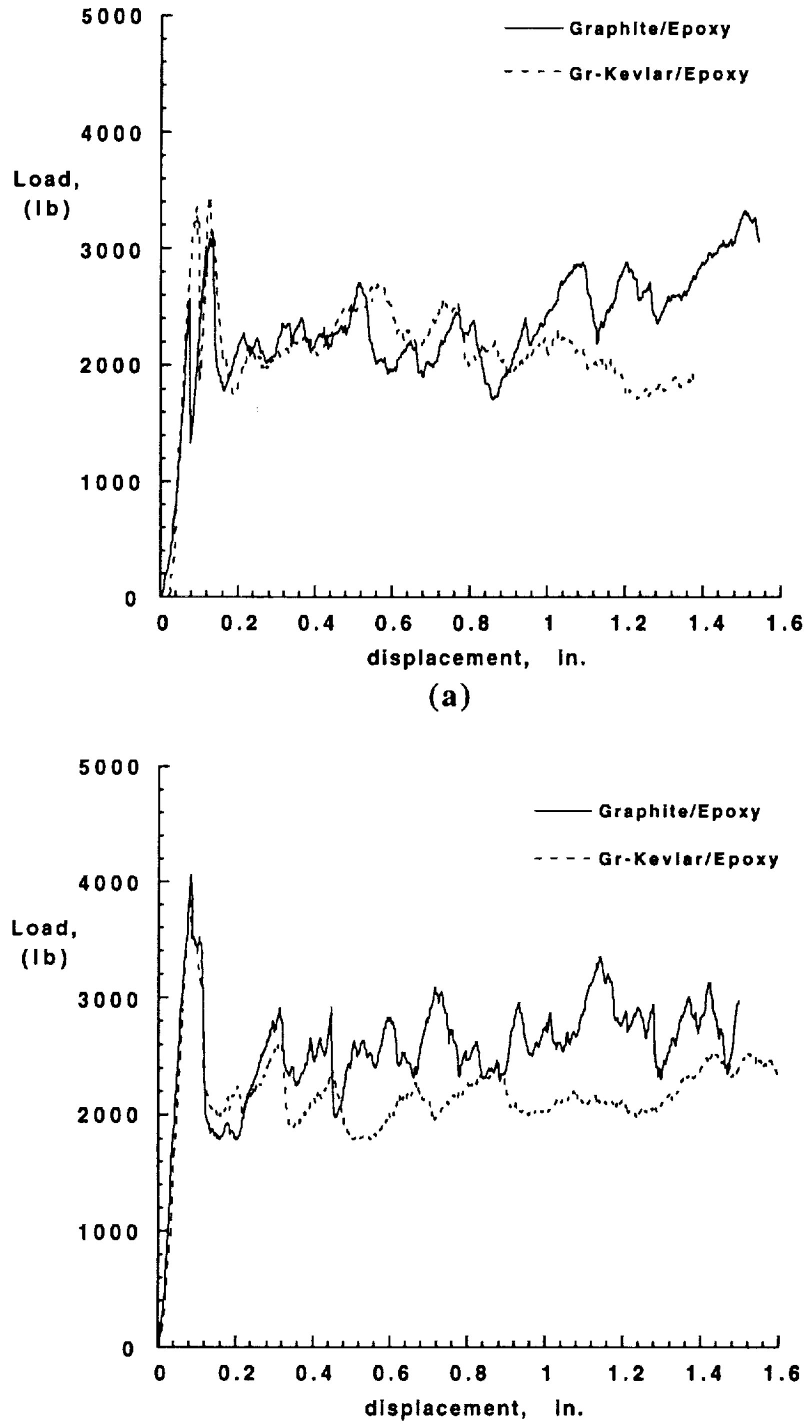


(a)



(b)

Figure 3.9 Summary of crushing data: AS4/Kevlar/3502 with **(a)** steeple and **(b)** notch trigger mechanism.



(a)

(b)

Figure 3.10 Comparison of crushing response of typical AS4/3502 and AS4/Kevlar/3502 baseline plates with **(a)** steeple and **(b)** notch triggers.

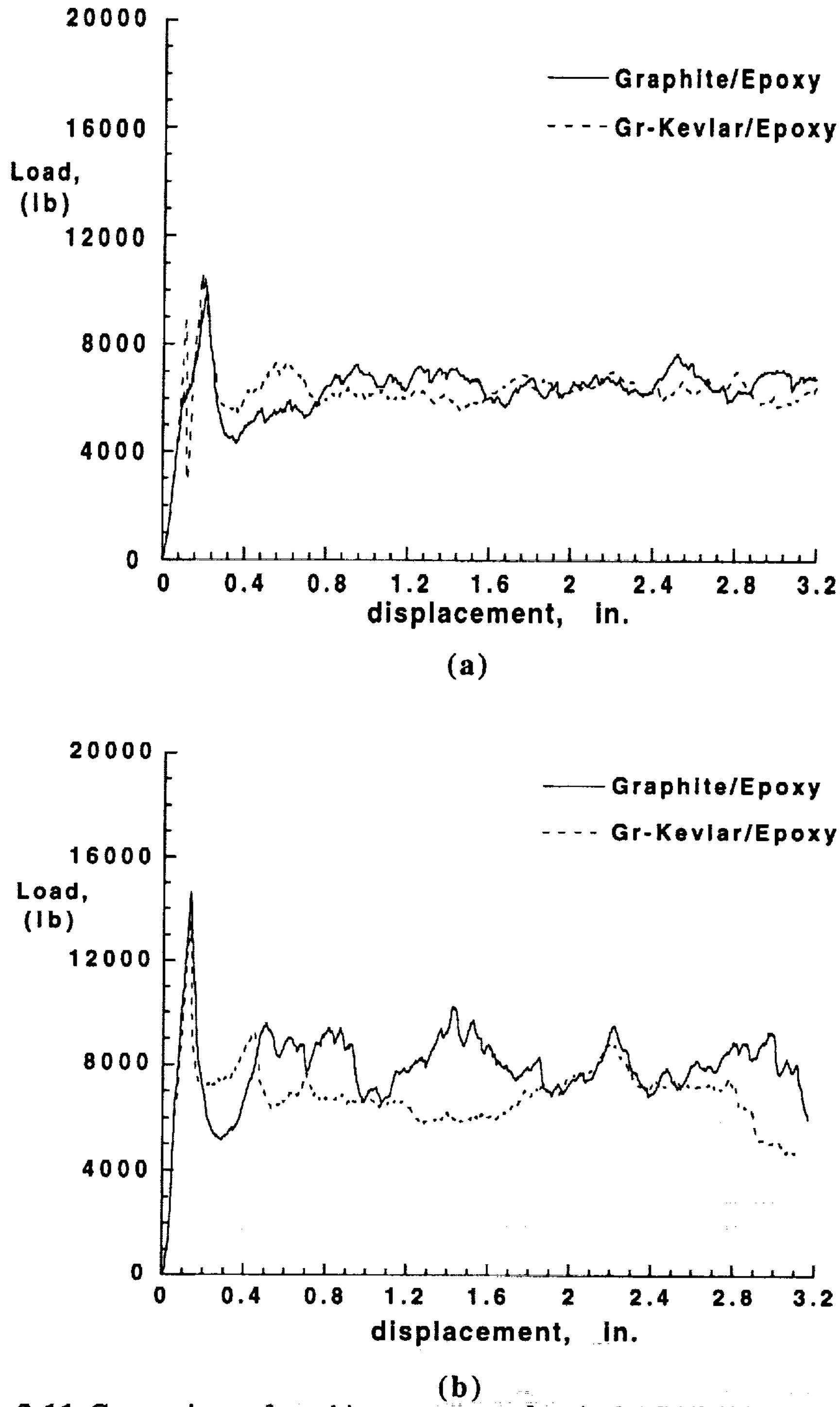


Figure 3.11 Comparison of crushing response of typical AS4/3502 and AS4/Kevlar/3502 ply-level-scaled plates with **(a)** steeple and **(b)** notch triggers.

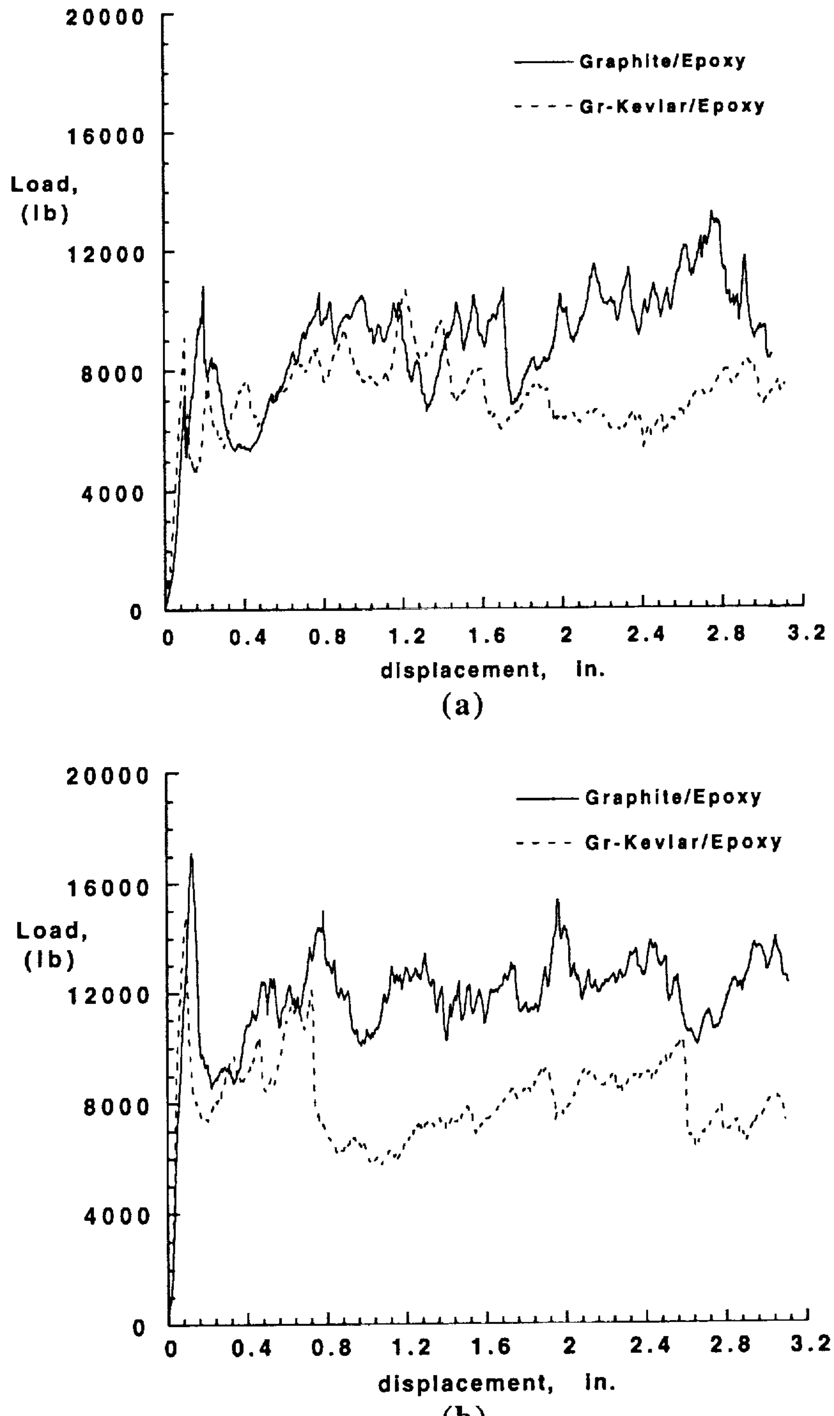
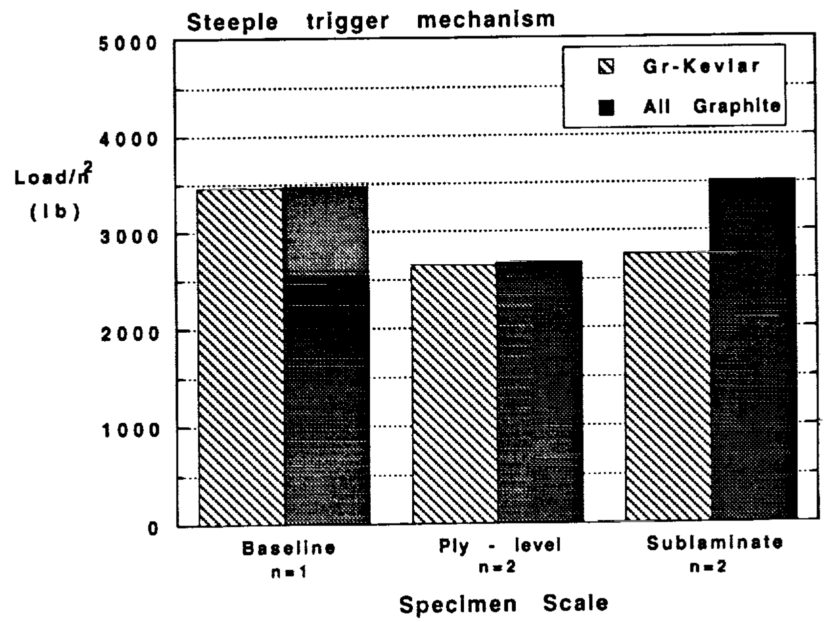
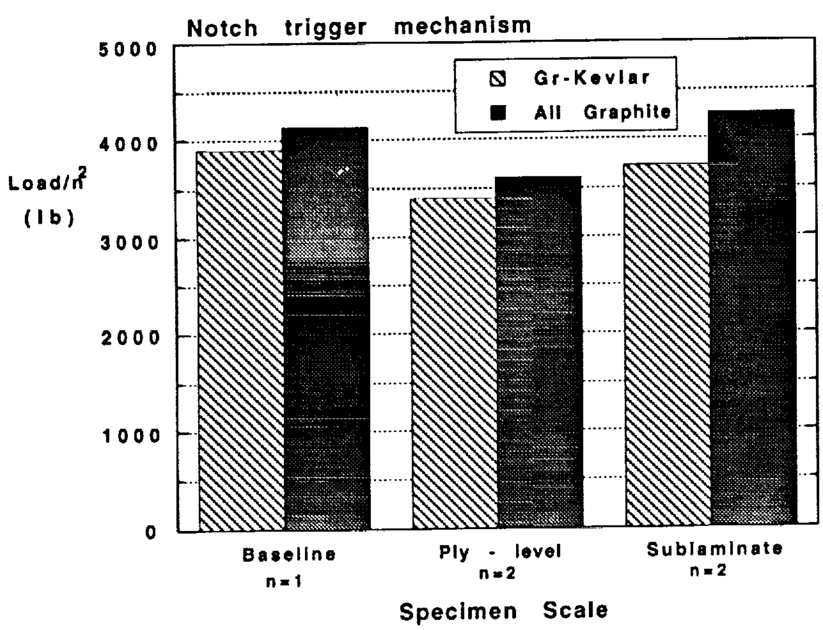


Figure 3.12 Comparison of crushing response of typical AS4/3502 and AS4/Kevlar/3502 sublaminate-scaled plates with (a) steeple and (b) notch triggers.



(a)



(b)

Figure 3.13 Comparison of peak crushing load for AS4/3502 and AS4/Kevlar/3502 with **(a)** steeple and **(b)** notch trigger mechanisms.

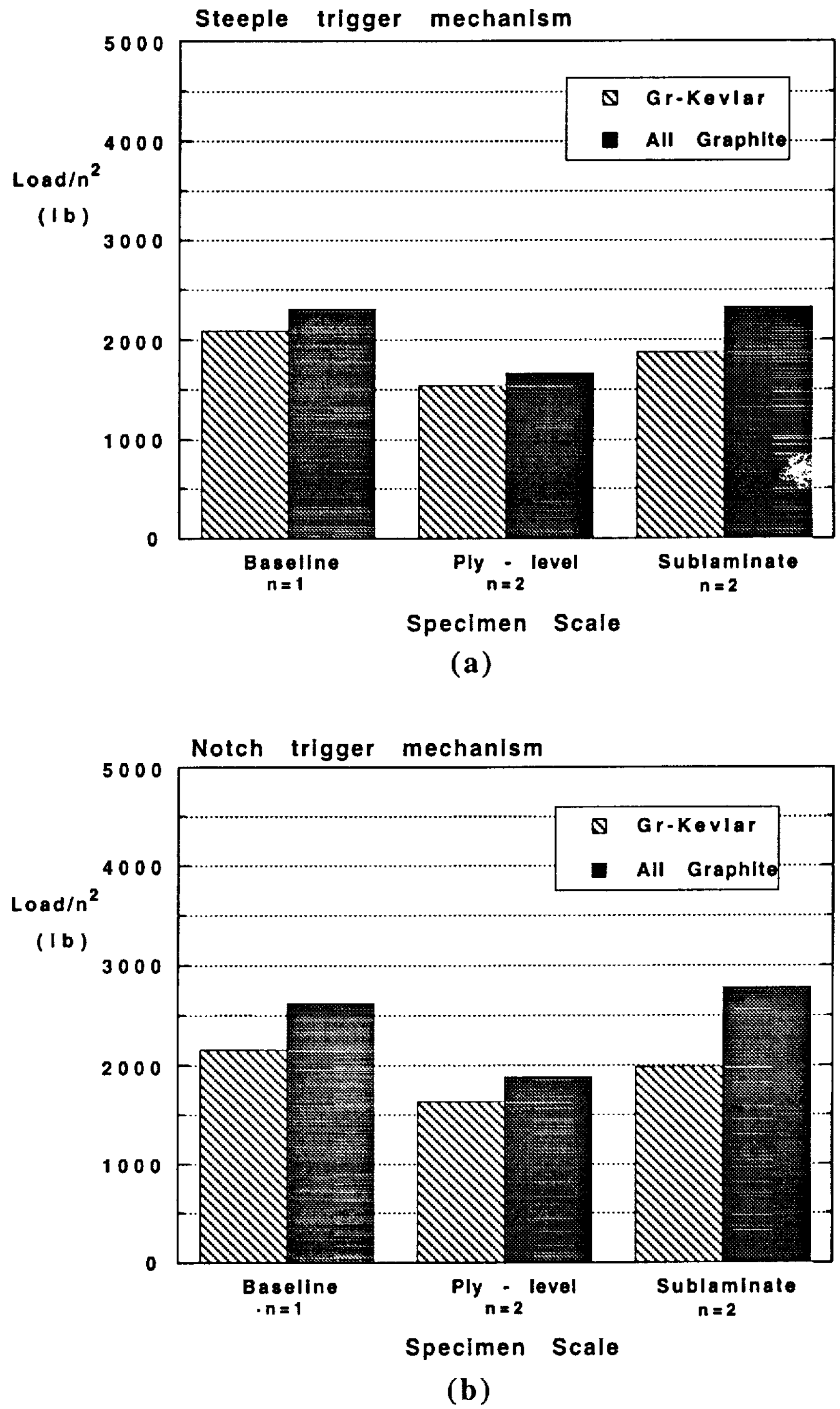
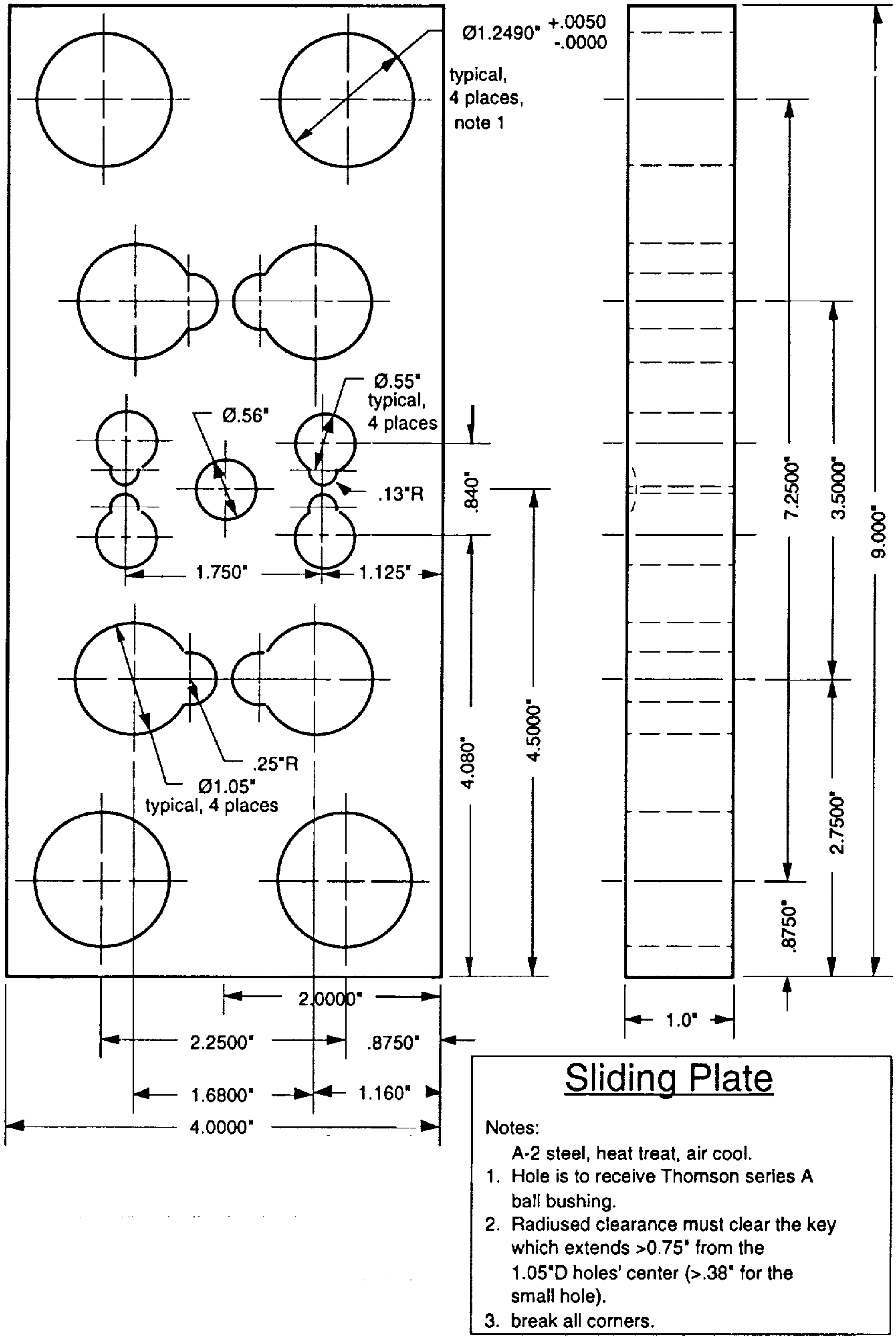


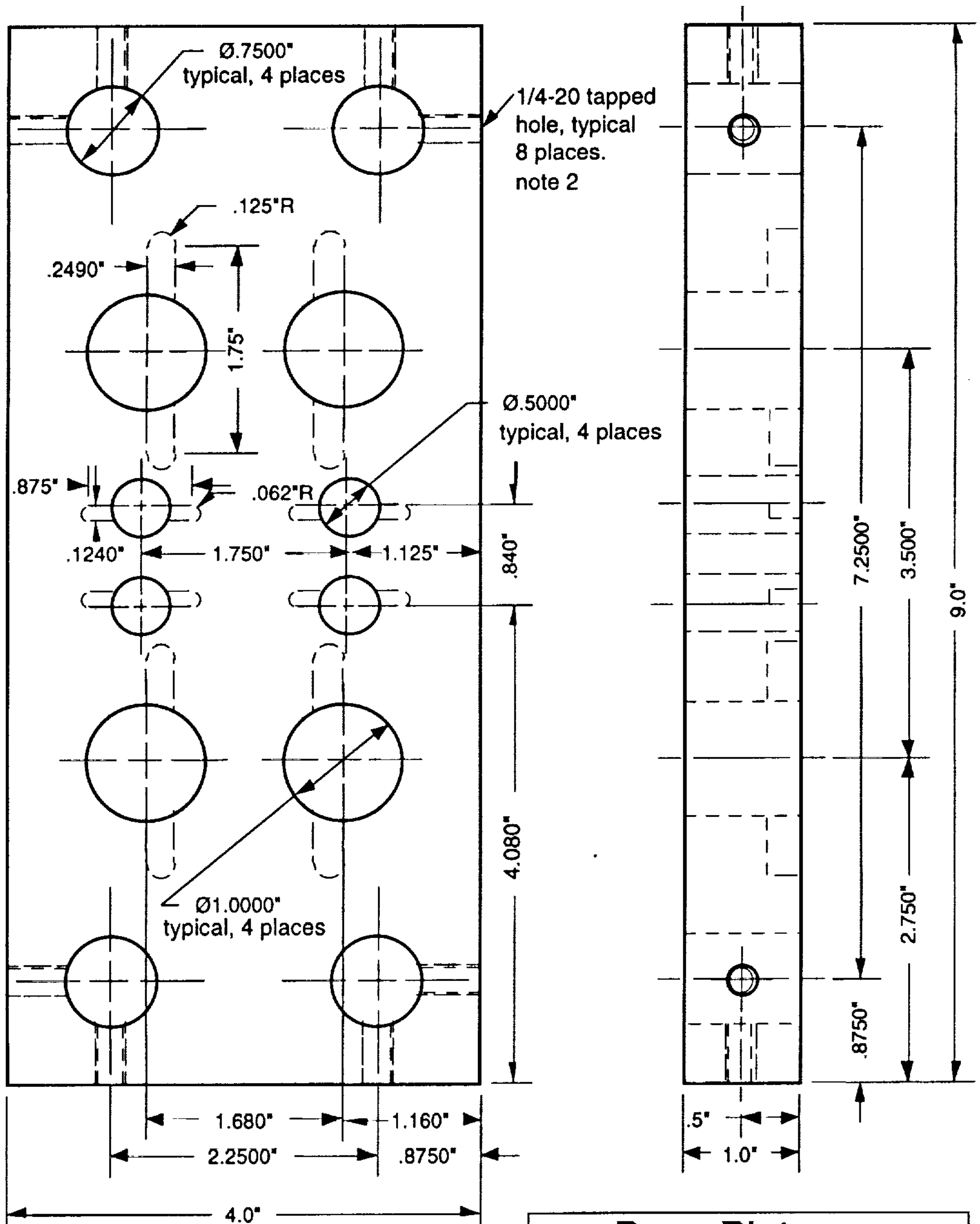
Figure 3.14 Comparison of average crushing load for AS4/3502 and AS4/Kevlar/3502 with (a) steeple and (b) notch trigger mechanisms.

7. APPENDIX

Engineering Drawings



A.1 Sliding plate.

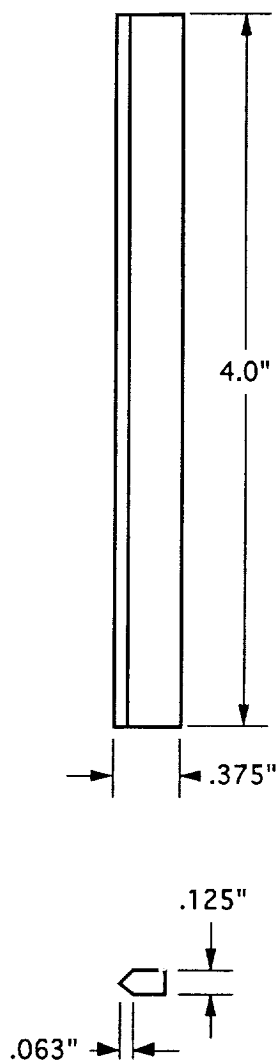


Base Plate

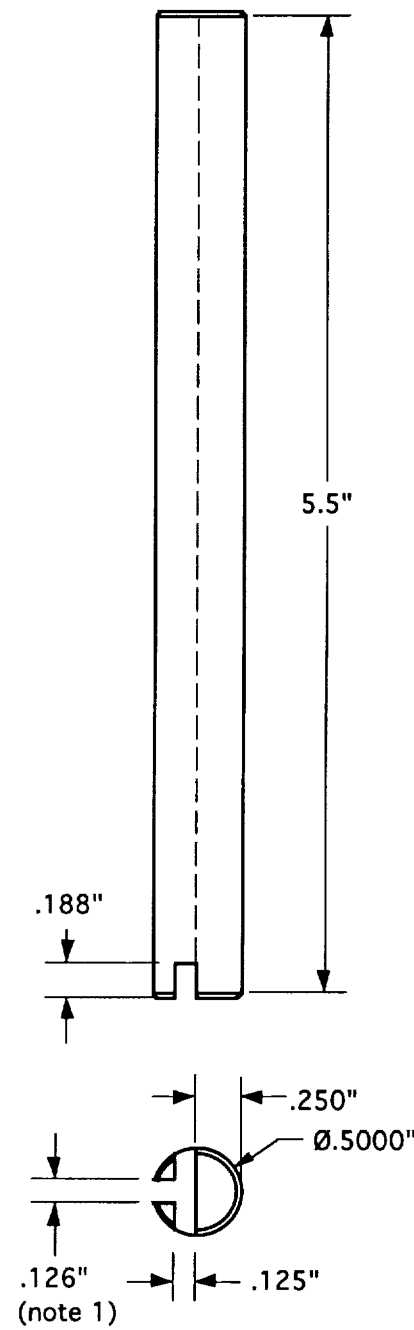
Notes: A-2 steel, heat treat, air cool
1. Key to be press fit into the slot and and ground flush.
2. 1/4"-20 tapped holes to receive 1/2" long set screws.

A.2 Base plate.

Knife Edge
(key stock, 4 req'd.)

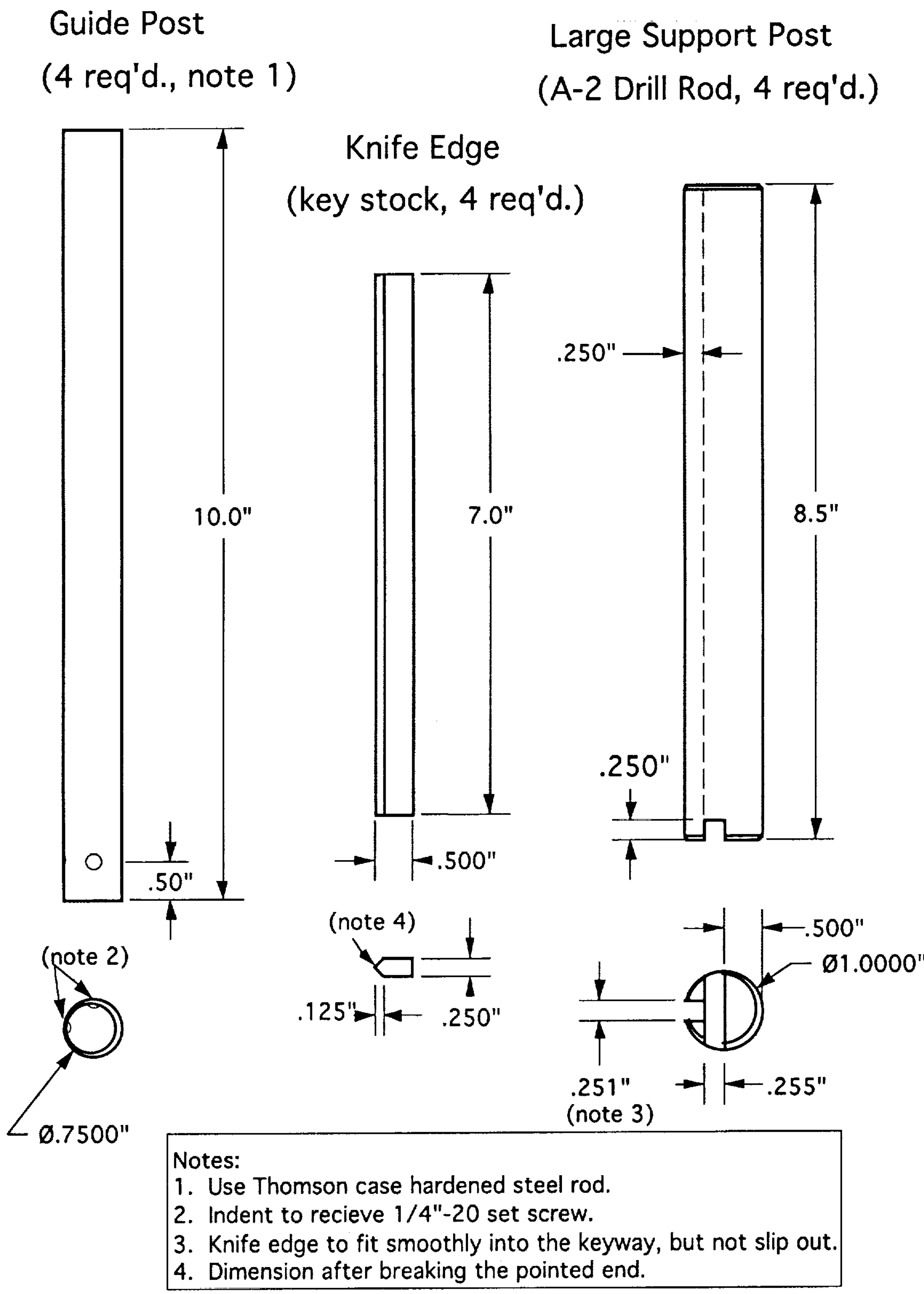


Small Support Post
(A-2 Drill Rod, 4 req'd.)

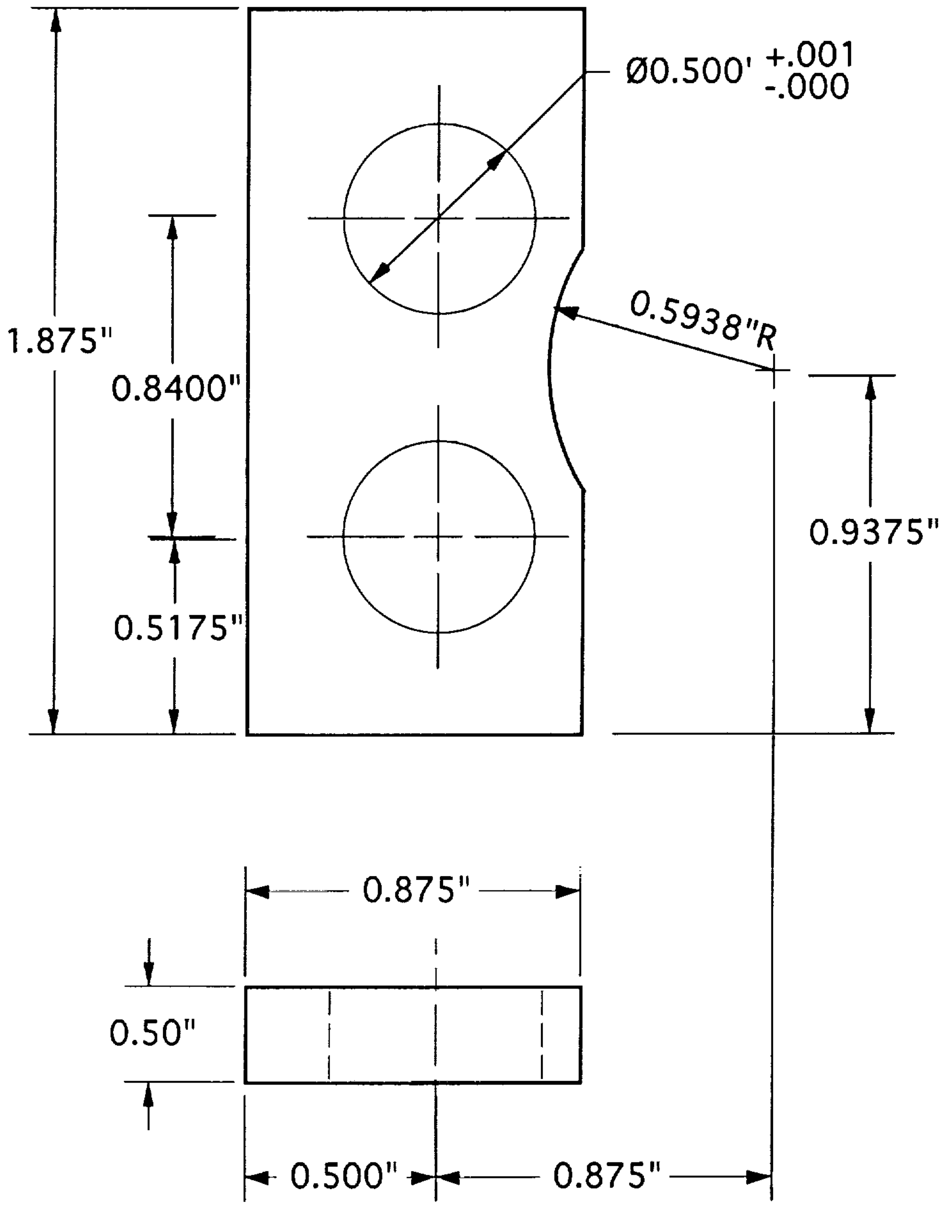


Notes:
1. Knife edge to fit smoothly into the keyway, but not slip out.

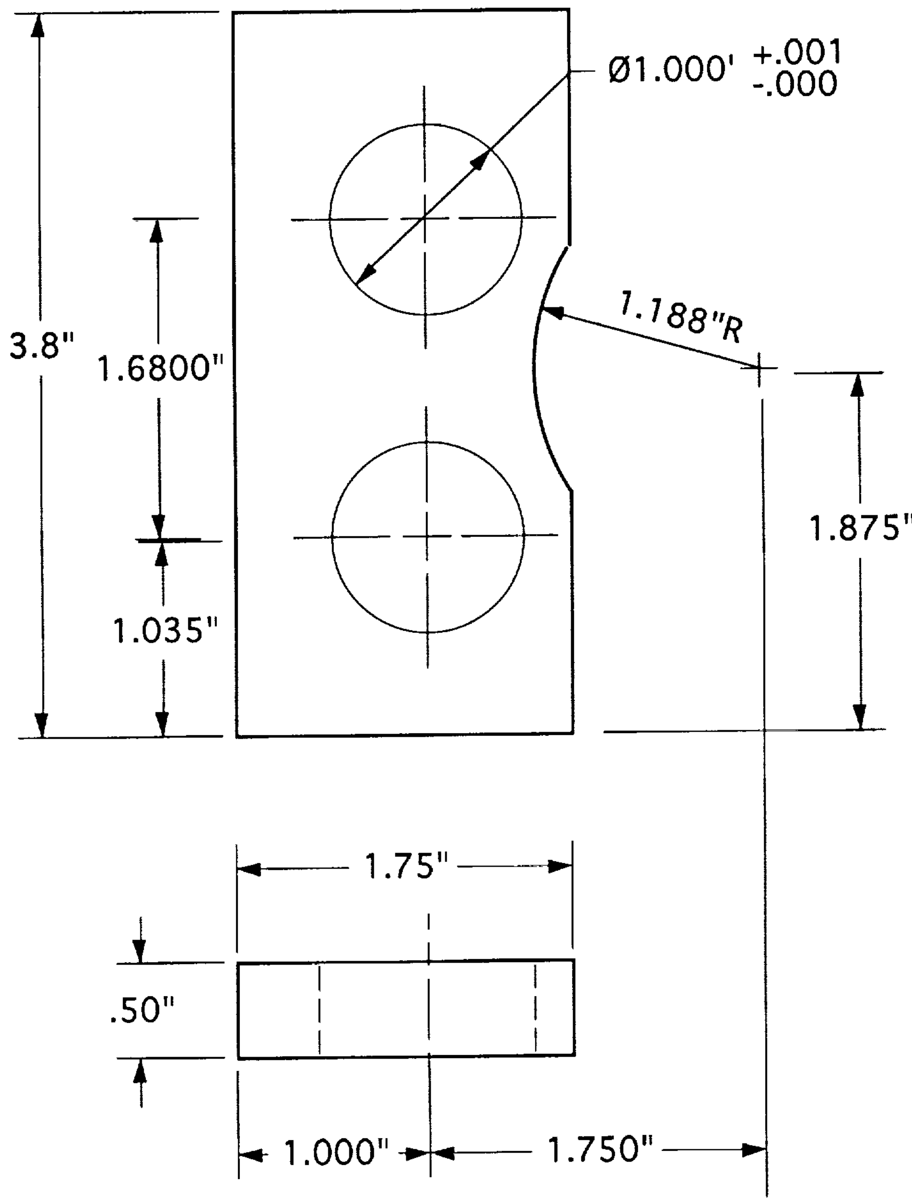
A.3 Small knife edge and support post.



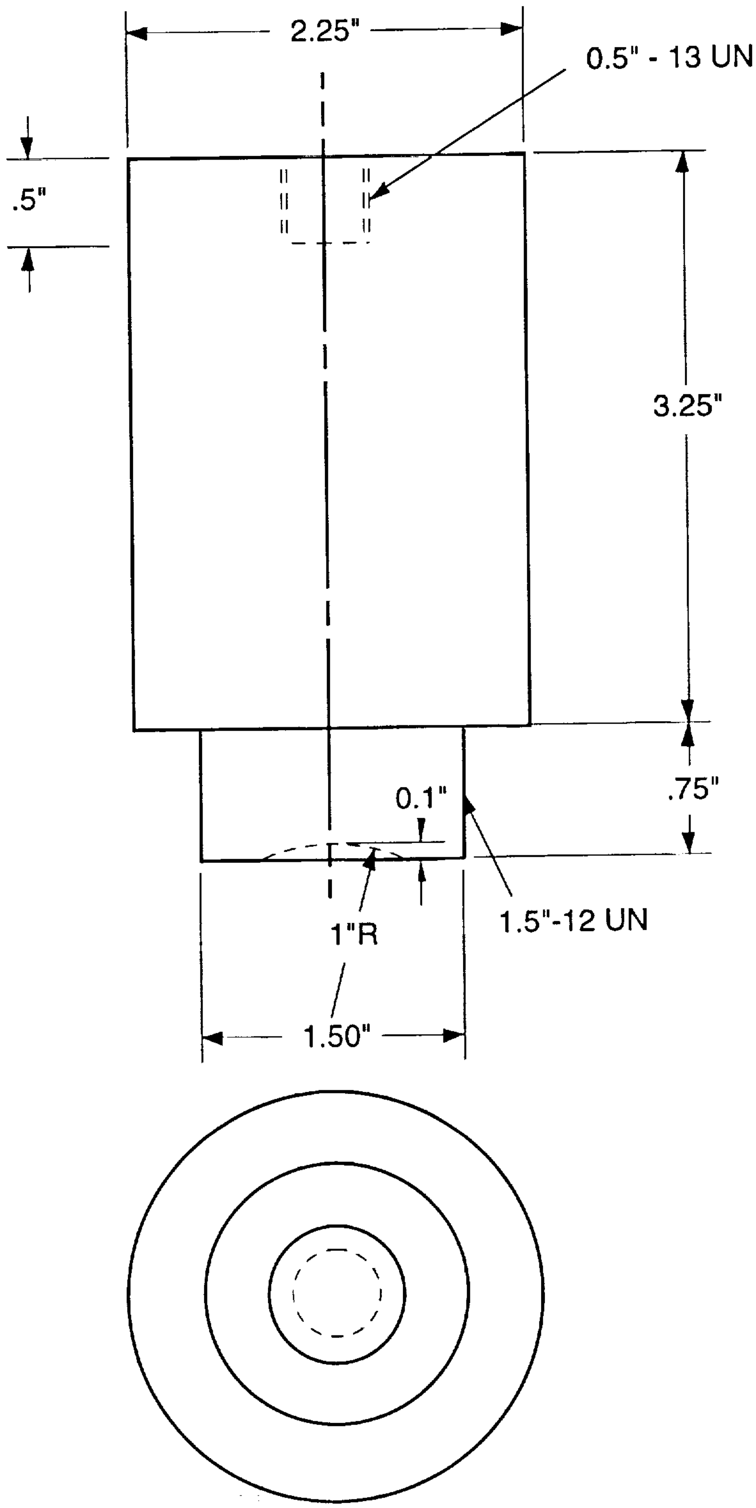
A.4 Large knife edge, guide post, and support post; four of each required.



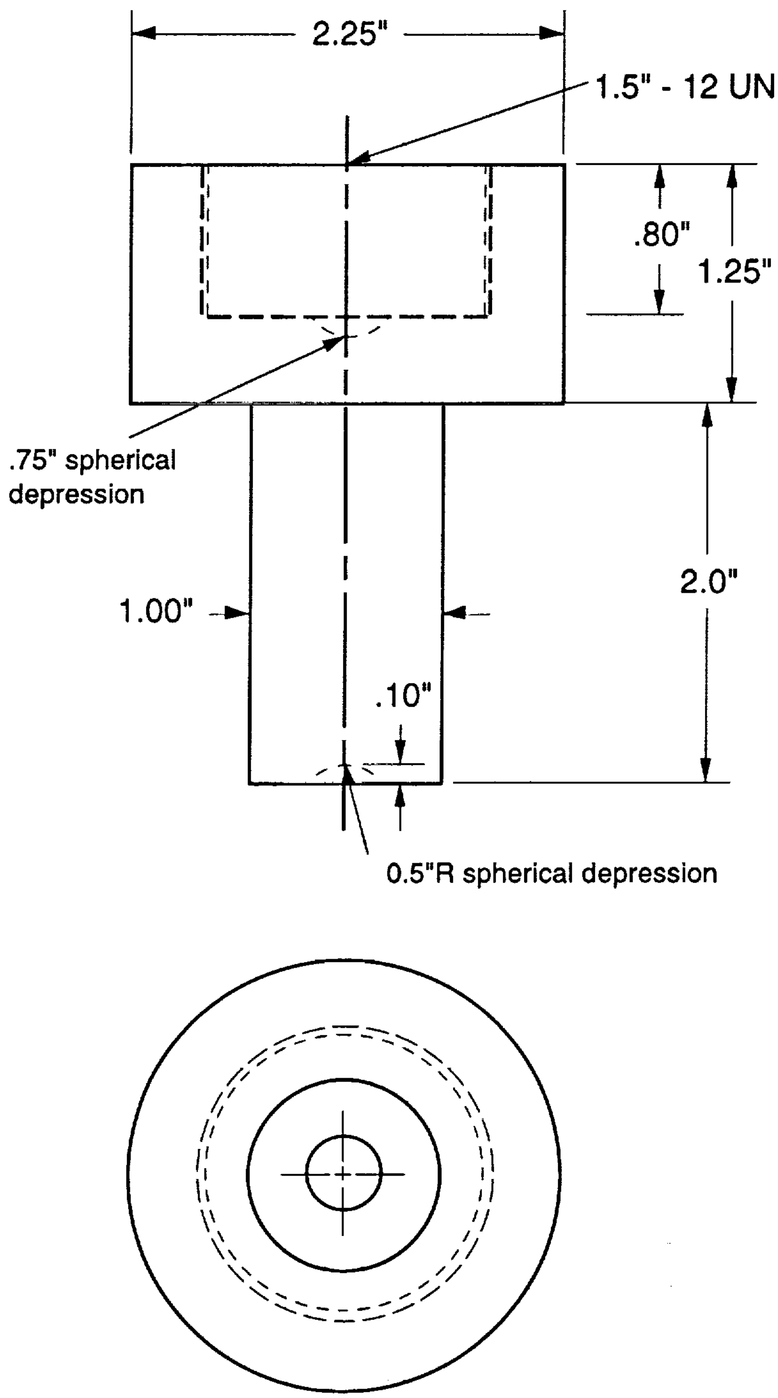
A.5 Small support post restraint, two required.



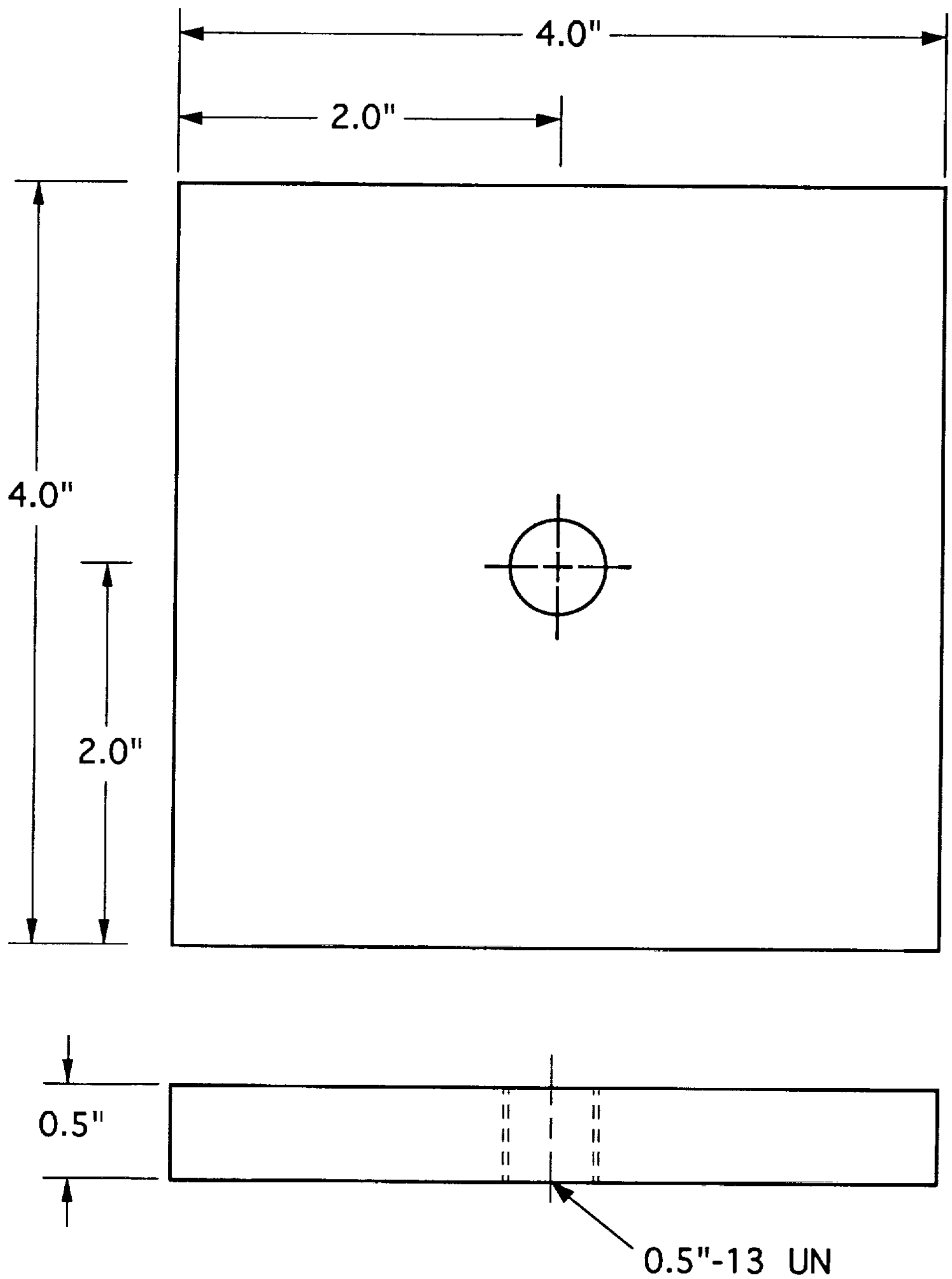
A.6 Large support post restraint, two required.



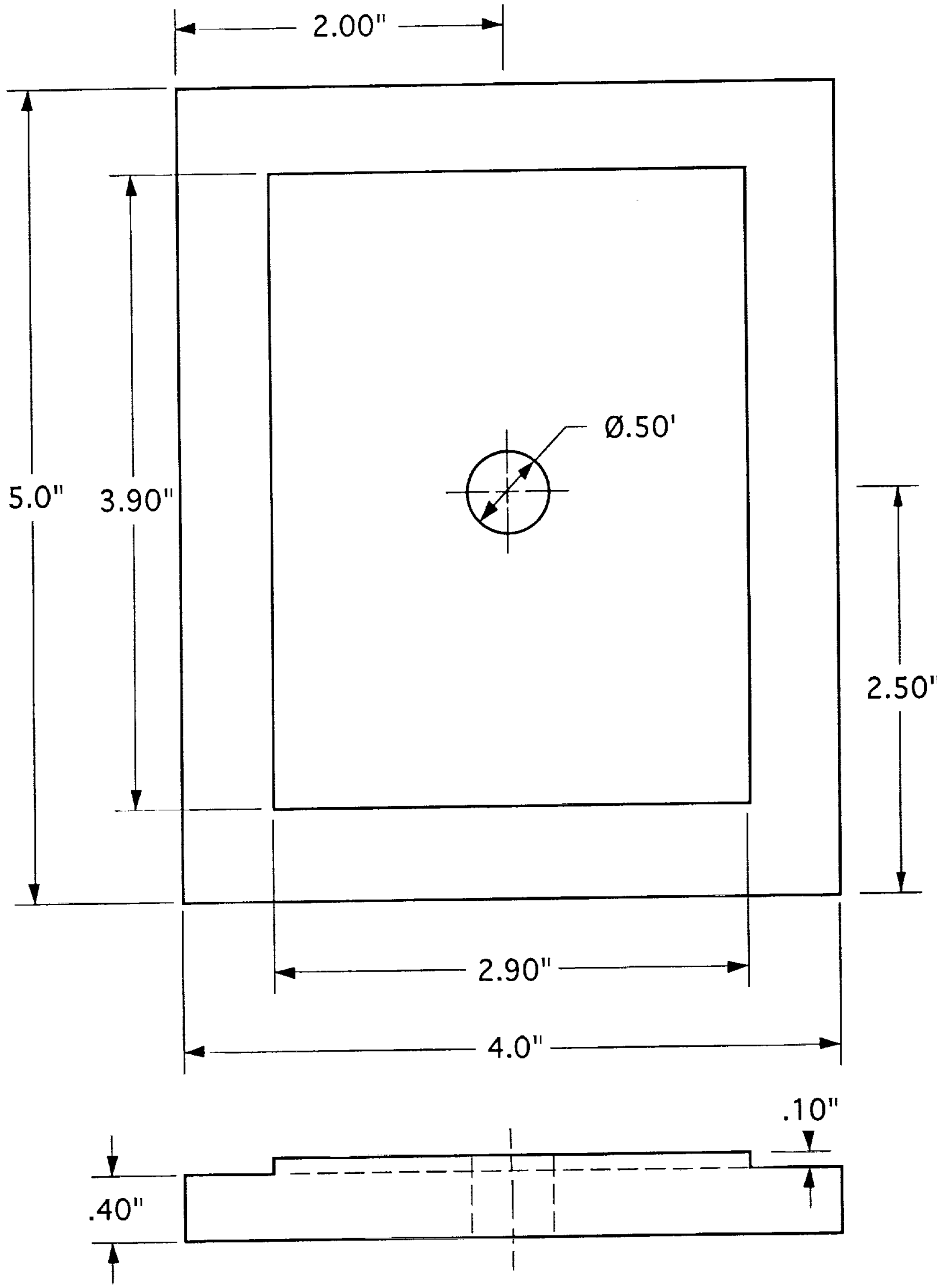
A.7 Load applicator rod.



A.8 Load applicatoı extension rod.



A.9 Load applicator retaining plate.



A.10 Load applicator centering plate.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
July 1993

3. REPORT TYPE AND DATES COVERED
Contractor Report

4. TITLE AND SUBTITLE
Design and Application of a Quasistatic Crush Test Fixture for Investigating Scale Effects in Energy Absorbing Composite Plates

5. FUNDING NUMBERS
G NAG1-343
WU 505-63-50-09

6. AUTHOR(S)
J. André Lavoie and John Morton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Virginia Polytechnic Institute and State University
Dept. of Engineering Science and Mechanics
225 Norris Hall
Blacksburg, VA 24061

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-4526

11. SUPPLEMENTARY NOTES
M.S. Thesis
Langley Technical Monitor: Karen E. Jackson

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited

Subject Category: 39

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
A crush test fixture for measuring energy absorption of flat plate specimens from an earlier study was redesigned to eliminate the problem of binding of the load transfer platen with the guide posts. Further modifications were to increase the stroke, and combine the two scaled text fixtures into one. This new crush text fixture was shown to produce load-displacement histories exhibiting well developed sustained crushing loads over long strokes.

An experimental study was conducted on two material systems: AS4/3502 graphite/epoxy, and a hybrid AS4-Kevlar/3502 composite. The effect of geometric scaling of specimen size, the effect of ply-level and sublaminate-level scaling of the stacking sequence of the full scale specimens, and the effect of trigger mechanism on the energy absorption capability were investigated.

The new crush test fixture and flat plate specimens produced peak and sustained crushing loads that were lower than obtained with the old crush text fixture. The trigger mechanism used influenced the specific sustained crushing stress (SSCS). The results of this study indicated that to avoid any reduction in the SSCS when scaling from the 1/2 scale to full scale specimen size, the sublaminate-level scaling approach should be used, in agreement with experiments on tubes. The use of Kevlar in place of the graphite 45^{o} plies was not as effective a means for supporting and containing the 0^{o} graphite plies for crushing of flat plates and resulted in a drop in the SSCS. This result did not correlate with that obtained for tubes.

14. SUBJECT TERMS
Energy Absorption, Crashworthiness, Composite Materials, Scale Effects, Trigger Mechanism Geometry

15. NUMBER OF PAGES
68

16. PRICE CODE
A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	